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Civilian Radioactive Waste Management System
Management and Operating Contractor

Emplacement Drift Invert-Low Steel Evaluation

TDR-EDS-ST-000002 REV 00

September 2000

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DISCLAIMER

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EXECUTIVE SUMMARY

This technical report evaluates and develops options for reducing the amount of steel in the emplacement drift invert. Concepts developed in the *Invert Configuration and Drip Shield Interface* were evaluated to determine material properties required for the proposed invert concepts.

Project requirements documents prescribe the use of a carbon steel frame for the invert with a granular material of crushed tuff as ballast.

The *Invert Configuration and Drip Shield Interface* developed three concepts:

- Modified Steel Invert with Ballast
- Steel Tie with Ballast Invert
- All-Ballast Invert

Analysis of the steel frame members, runway beams, and guide beams, for the modified steel invert with ballast, decreased the quantity of steel in the emplacement drift invert, however a substantial steel support frame for the gantry and waste package/pallet assembly is still required.

Use of one of the other two concepts appears to be an alternative to the steel frame and each of the concepts uses considerably less steel materials.

Analysis of the steel tie with ballast invert shows that the bearing pressure on the ballast under the single steel tie, C 9x20, loaded with the waste package/pallet assembly, drip shield, and backfill exceeds the upper bound of the allowable bearing capacity for tuff used in this study. The single tie, C 10x20, will also fail for the same loading condition except for the tie length of 4.2 meters and longer. Analysis also shows that with two ties, C 9 or 10x20's, the average ballast pressure is less than the allowable bearing capacity. Distributing the waste package/pallet, drip shield, and backfill loads to two steel ties reduces the contact bearing pressure. Modifying the emplacement pallet end beams to a greater width, reducing the tie spacing, and increasing the width of the ties would ensure that the pallet beams are always supported by two steel ties. Further analysis is required to determine compatible tie size and spacing and pallet beam width. Testing is also required to determine the bearing capacity of the tuff materials.

Analysis of the all-ballast invert shows that the waste package/pallet assembly, as currently designed, can be supported by the compacted crushed tuff. The drip shield and related backfill loads cannot be supported by the compacted crushed tuff because of the narrow base angle that currently supports the drip shield. Increasing the width of the base angle of the drip shield will better distribute the drip shield and backfill load to the compacted crushed tuff. Testing is required to determine the bearing capacity of the tuff materials. Emplacement/retrieval equipment will also require analysis and development to be compatible with the all-ballast invert.

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CONTENTS

Page

FIGURES

Page

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TABLES

Page

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ACRONYMS

ABP	Average Ballast Pressure
BC	Bearing Capacity
CPA	Controlled Project Assumption
SSC	Structures, Systems, and Components
TBD	To Be Determined
TBM	Tunnel Boring Machine
TBV	To Be Verified
WP	Waste Package

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1. PURPOSE

1.1 OBJECTIVE

The objective of this technical report is to evaluate and develop options for reducing the amount of steel in the emplacement drift invert. Concepts developed in the *Invert Configuration and Drip Shield Interface* (CRWMS M&O 2000a) will be evaluated to determine material properties, i.e., dimensions, weights, allowable stresses for structural materials and bearing capacity for ballast materials, required for the proposed invert concepts.

1.2 SCOPE

This technical report will evaluate existing conceptual designs for the emplacement drift invert to develop options for reducing the amount of steel currently proposed for the invert support structure. Evaluation will focus on optimizing the effective use of steel materials for the emplacement drift invert, with the goal of reducing the use of steel materials to the extent possible. Material dimensions will be determined as necessary. Bearing capacity of proposed ballast material will be evaluated to assess suitability for use in the invert. Design loads imposed on the emplacement drift invert will include loads from construction, waste package emplacement/retrieval (CRWMS M&O 2000b), drip shields (CRWMS M&O 2000c), performance confirmation and monitoring equipment, as well as any potential backfill and related emplacement equipment (CRWMS M&O 2000d). Primary tasks shown in Development Plan TDP-EDS-ST-000002, *Emplacement Drift Invert-Low Steel Evaluation* (CRWMS M&O 2000l) include evaluating the potential reduction of steel materials in the emplacement drift invert and refining emplacement drift invert support concepts previously developed in the *Invert Configuration and Drip Shield Interface* (CRWMS M&O 2000a).

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2. QUALITY ASSURANCE

The QAP-2-0 *Activity Evaluation for Ex-Container and Backfill WP# 12012124M8*, (CRWMS M&O 1999) has determined that this activity is subject to the requirements of *Quality Assurance Requirements and Description* (DOE 2000). Unqualified data and input requiring confirmation will be identified as to be verified/to be determined, and will be tracked in accordance with AP-3.15Q, *Managing Technical Product Inputs*. This work activity has been evaluated in accordance with AP-SV.1Q, *Control of the Electronic Management of Information*. The review process for this technical evaluation will be in accordance with AP-2.14Q, *Review of Technical Products*. The final document will be approved in accordance with Section 5.5 of AP-3.11Q, *Technical Reports*.

This technical report evaluates possible inputs and design alternatives, and directly supports system documents that will be used in the Site Recommendation. This technical report, therefore, is subject to Level 3 change control as defined in AP-3.11Q, *Technical Reports,* Section 5.2d, and will impact the technical baseline controlled by AP-3.4Q, *Level 3 Change Control.*

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3. METHOD

This technical report reviews existing analyses, reports, drawings and other documents to determine relevant aspects that have the potential to contribute to and enhance the evaluation of the design concepts for the emplacement drift invert. Analytical methods of relevant engineering concepts with arithmetic computation and logic will be used.

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4. INPUTS

This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the input information quality may be confirmed by review of the Document Input Reference System database (AP-3.15Q, Section 5.5.1.d).

4.1 PARAMETERS

Parameters used as inputs are referenced from codes and standards and are accepted data and therefore, are appropriate for their intended purpose in this technical report.

4.1.1 Steel Material Properties

Steel material to be used for the steel frame and support ties of the emplacement drift invert concepts is discussed in Section 6.4.1 and related materials properties are shown below:

- ASTM A 36/A 36M: Yield point of 250 MPa (36 ksi), maximum carbon content of 0.26 percent.

- ASTM A 240/A 240M: Minimum carbon content of 0.01 (yield point ranging from 275 MPa (40 ksi) to 415 MPa (60 ksi)), maximum carbon content of 0.15 (yield point ranging from 205 MPa (30 ksi) to 345 MPa (50 ksi)).

- ASTM A 242/A 242M: Maximum carbon content of 0.15 percent, yield point of 345 MPa (50 ksi), atmospheric corrosion-resistance index of 6.0 or higher.

- ASTM A 572/A572M: Minimum yield point of 290 MPa (42 ksi) (carbon 0.21 percent), Maximum yield point of 450 MPa (65 ksi) (carbon 0.26 percent).

- ASTM A 588/A 588M: Maximum carbon content of 0.15 percent (Grade C), yield point of 345 MPa (50 ksi), atmospheric corrosion-resistance index of 6.0 or higher.

- ASTM A 709/A 709M: Maximum carbon content for plate of 0.11 percent (Grade HPS 70W (HPS 485 W)), yield point of 485 MPa (70 ksi), atmospheric corrosion-resistance index of 6.0 or higher.

Used in Sections 6.4.1 and 7.2.1.

4.1.2 Ballast Material Properties

Recommendations for strength and durability of crushed rock ballast and the related testing specifications according to the *Manual for Railway Engineering* (AREA 1997, p. 1-2-12, Table 2-1) for limestone as a representative material are as follows:

- Bulk Specific Gravity: 2.60 min. (ASTM C 127)
- Absorption Percent: 2.0 max. (ASTM C 127)
- Clay Lumps and Friable Particles: 0.5 % max. (ASTM C 142)
- Degradation: 30% max. (see Note 1 below)
- Soundness (Sodium Sulfate) 5 Cycles: 5.0 % max. (ASTM C 88)
- Flat and/or Elongated Particles: 5.0 % max. (ASTM D 4791)
- Percent Material Passing No. 200 Sieve: 1.0 % max. (ASTM C 117)

Note 1: Materials having gradations containing particles retained on the 1 inch sieve shall be tested by ASTM C 535. Materials having gradations with 100% passing the 1 inch sieve shall be tested by ASTM C 131.

Used in Section 7.3.2.

4.1.3 Design Dead and Live Loads

Dead and live loads used for evaluation of the emplacement drift invert are shown below:

- Waste package/pallet assembly: Waste package, 85,000 kg (85 MT) (maximum) + Pallet, 3,000 kg (3 MT) = 88 MT (CRWMS M&O 2000g, Section 6.2).

- Drip shield: 4203 kg/(5.195+0.610)m = 724.03 kg/m (CRWMS M&O 2000k, Sketch SK-0148 REV 05, page II-1)

- Backfill (if used): Overton sand, bulk density 1488 kg/m^3 (CRWMS M&O 2000d, Table 1).

- Waste emplacement/retrieval equipment: Gantry, 60 MT (CRWMS M&O 2000g, Section 6.3.4, page 53 of 77).

- Drip shield pressures from backfill and loose rock mass: 146 kPa (21.2 psi) (CRWMS M&O 2000c, Table 5.2-1).

Used in Sections 4.4.1, 6.2, 7.1.1, 7.2 and 7.2.1.

4.1.4 Seismic Forces

Subsurface seismic forces used for evaluation of the emplacement drift invert are: Subsurface horizontal motion of 0.242 g and subsurface vertical motion of 0.182 g (CRWMS M&O 2000b, Additional Assumption 2.2.2.2) with a multiplication factor of 1.5 (NRC 1987, NUREG-0800, Section 3.7.2, paragraph II.B.1.b(3)). Used in Sections 4.4.2, 7.1.2 and 7.2.1.

4.2 CRITERIA

4.2.1 Emplacement Drift System Description Document Design Criteria

The following design criteria applicable to this report are from the *Emplacement Drift System Description Document* (CRWMS M&O 2000e). Not all design criteria identified in this reference have been used in this report.

4.2.1.1 System Performance Criterion 1.2.1.8

For 10,000 years, the system shall allow free-liquid-phase water, from events identified in CRWMS M&O 2000e (Table 1) to drain out of emplacement drifts, via the emplacement drift floor. Events for the emplacement drift inflow (CRWMS M&O 2000e, Table 1) include:

- Water Volume: 2 cubic meters per meter of emplacement drift (TBV-284) [To Be Verified]
- Event Duration: 1 week (TBV-284)
- Event Frequency: 1 event per year (TBV-284)

Used in Section 7.3.2.

4.2.1.2 System Performance Criterion 1.2.1.9

The invert structural members shall be composed of carbon steel. Used in Section 6.4.1.

4.2.1.3 System Performance Criterion 1.2.1.11

The invert ballast material shall be granular. (See, also, Section 4.3.2.) Used in Section 6.4.2.

4.2.1.4 System Performance Criterion 1.2.1.22

The invert and [waste package] WP emplacement pallet shall provide structural support for the SSCs [Structures, Systems, and Components] as identified in CRWMS M&O 2000e (Table 2). SSCs supported by the invert and pallet (CRWMS M&O 2000e, Table 2) include:

- Waste packages
- Drip shields (invert only)
- Backfill (invert only) [If used.]
- Waste Emplacement/Retrieval System mobile equipment (SSCs entering emplacement drifts, invert only)
- Backfill Emplacement System mobile equipment (SSCs entering emplacement drifts, invert only) (If used)

- Performance Confirmation Emplacement Drift Monitoring System mobile equipment (SSCs entering emplacement drifts, invert only)

- Subsurface Emplacement Transportation System (SSCs within emplacement drifts, invert only)

- Subsurface Excavation System (SSCs placing inverts, as necessary, invert only)

Used in Sections 6.2 and 7.2.1.

4.2.1.5 Codes and Standards Criterion 1.2.6.1

Design of steel SSC's shall be in accordance with "Manual of Steel Construction Allowable Stress Design" or "Manual of Steel Construction Load and Resistance Factor Design." Used in Section 7.2.1.

4.2.1.6 Codes and Standards Criterion 1.2.6.2

The system shall comply with the applicable assumptions contained in the "Monitored Geologic Repository Project Description Document." (CRWMS M&O 2000j) Used in Section 4.3.

4.2.1.7 System Interfacing Criterion 1.2.4.7

The system shall accommodate a minimum spacing of 10 cm between WPs [waste packages] within individual emplacement drifts. Used in Sections 6.2 and 7.2.1.

4.3 CONTROLLED PROJECT ASSUMPTIONS

The following Controlled Project Assumptions (CPAs) applicable to this report are from the *Monitored Geologic Repository Project Description Document* (CRWMS M&O 2000j) (Section 4.2.1.6). Not all assumptions identified in this reference have been determined to be applicable to this report.

4.3.1 CPA 026 - Subsurface Configuration for Water Drainage

The repository subsurface layout will be configured for postclosure water drainage such that: Water entering the emplacement drifts can drain directly into the surrounding host rock without draining along the drift for collection in a centralized location. (This assumption does not encompass general flooding of the facility). (This controlled project assumption is included in System Performance Criterion 1.2.1.8 in Section 4.2.1.1.) Used in Section 7.3.2.

4.3.2 CPA 039 – Enhanced Design Alternative II Design Definition for Performance Assessment Department, Waste Package Department, and Subsurface Facilities Department

Performance assessment modeling will use the design constraints and applicable performance criteria in Section 5.0 of this PDD [Project Description Document] (CRWMS M&O 2000j) to define design concepts and parameters implementing EDA II. Performance assessment will assume that the design parameters are equal to values stated in these constraints and criteria as nominal or limiting values.

In addition, the Performance Assessment Department, the Waste Package Department, and the Subsurface Facilities Department will assume for SR [Site Recommendation], that the:

- Invert ballast material is crushed tuff. (This part of the assumption is in addition to System Performance Criterion 1.2.1.11 in Section 4.2.1.3 and defines the type of granular ballast material.) Used in Sections 6.4.2, 7.3 and 7.3.2.

- Free-standing drip shield is of "mailbox" shape and with uninterrupted coverage for the entire length of the emplacement drift. (This part of the assumption is in addition to System Performance Criterion 1.2.1.22 in Section 4.2.1.4 and defines the extent of coverage the drip shields must provide.) Used in Section 6.2.

4.4 OTHER ASSUMPTIONS

4.4.1 Weight of Miscellaneous Emplacement and Monitoring Equipment

Weights of performance confirmation emplacement drift monitoring equipment and backfill emplacement equipment, if used, have not been determined. For this technical report it is assumed that the weight of such equipment will not exceed the weight of the emplacement gantry plus the weight of a waste package/pallet assembly. Weight of the waste package plus pallet is 85 MT plus 3 MT (CRWMS M&O 2000g, Section 6.2) or 88 MT total, Section 4.1.3. Weight of the emplacement gantry is 60 MT (CRWMS M&O 2000g, Section 6.3.4, page 53 of 77) Section 4.1.3. Combined total weight of the emplacement gantry carrying a waste package is 148 MT. Used in Sections 6.2 and 7.1.1.

4.4.2 Seismic Load

Vertical and horizontal accelerations due to a seismic event need to be verified to validate the design of the bottom/side lift gantry and other subsurface mobile equipment that handles WPs. Subsurface seismic forces are currently based upon a horizontal motion of 0.242 g and a vertical motion of 0.182 g (CRWMS M&O 2000b, Additional Assumption 2.2.2.2).

Section 5.3 (CRWMS M&O 2000g) discusses the use of the equivalent static load method for applying seismic forces using a multiplication factor of 1.5 applied to the horizontal and vertical seismic accelerations in accordance with NUREG-0800, Section 3.7.2, paragraph II.B.1.b(3) (NRC 1987).

The above seismic accelerations and multiplication factor were used to develop the bottom/side lift gantry concept in CRWMS M&O 2000g. It is appropriate for the analysis of the emplacement drift invert concepts in this technical report to use a similar seismic loading. Used in Sections 4.1.4, 7.1.2, 7.2.1 and 7.3.3.2.

5. USE OF COMPUTER SOFTWARE

No computer software was used for technical analysis or for the preparation of this evaluation. Only personal computers with associated printers and computer-aided drafting and design equipment, and word processing software were used.

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6. PROPOSED EMPLACEMENT DRIFT INVERT CONCEPTS

6.1 GENERAL

The Emplacement Drift System structural support hardware (emplacement drift invert and WP [waste package] emplacement pallet) and performance-enhancing barriers (drip shields and invert ballast) are interrelated as part of the Engineered Barrier System, (CRWMS M&O 2000e, p. 6). The Emplacement Drift System limits the release and transport of radionuclides from the Waste Package to the Natural Barrier following waste emplacement. In this design, the waste package emplacement pallet and drip shield rest directly on the emplacement drift invert. Backfill, if used, (CRWMS M&O 2000j, Section 5.2.9) will be placed over the drip shield.

Emplacement drift invert design concepts were developed in *Invert Configuration and Drip Shield Interface* (CRWMS M&O 2000a). Figures 5 and 6 (CRWMS M&O 2000a) show elevation and perspective views of the modified steel invert with ballast. Figures 7 and 8 (CRWMS M&O 2000a) show elevation and perspective views of the steel tie with ballast invert. Figures 9 and 10 (CRWMS M&O 2000a) show elevation and perspective views of the all-ballast invert. These figures show the relationship between the invert/ballast, the waste package/emplacement pallet, and the drip shield for the concepts that will be evaluated in this technical report to develop options for reducing the amount of steel materials in the emplacement drift invert. Clearly, the all-ballast invert shown in Figures 9 and 10 (CRWMS M&O 2000a) needs no evaluation to reduce the use of steel materials.

Concepts shown for the emplacement drift invert in Figures 5, 6, 7 and 9 (CRWMS M&O 2000a) have steel members with sizes designated as an allowance. These steel members will be evaluated in Section 7.2 to determine member sizes based on current information.

6.2 INVERT DESIGN LOADS

Loads on the emplacement drift invert will include dead loads from the waste package/pallet assemblies, the drip shields, and any backfill (Section 4.2.1.4). Design of the Monitored Geologic Repository shall not preclude the options of physically installing the emplacement drift backfill during the repository closure phase (CRWMS M&O 2000j, Design Constraint 5.2.9). Also included will be live loads from the waste emplacement/retrieval equipment, the performance confirmation emplacement drift monitoring equipment, and any backfill related emplacement equipment (CRWMS M&O 2000j, Design Constraint 5.2.10) (Section 4.2.1.4). Weights of the performance confirmation emplacement drift monitoring equipment and backfill related emplacement equipment will not exceed the weight of emplacement gantry plus the weight of a waste package/pallet assembly (Section 4.4.1). Loads created by seismic activity will also be determined.

Dead loads from the waste package/pallet assemblies will accommodate a minimum spacing of 10 cm between waste packages within individual emplacement drifts (Section 4.2.1.7). Dead loads from the drip shields will include a free-standing drip shield of "mailbox" shape with uninterrupted coverage (i.e., loading) for the entire length of the emplacement drift (CPA 039, Section 4.3.2), with a drip shield load of 724 kg/m (Section 4.1.3).

Dead load from backfill that may be placed in the emplacement drift must be considered. The dead load from the backfill will be transmitted to the drift invert through the drip shield and by direct contact with the drift invert. The backfill material load of 1488 kg/m^3 (Section 4.1.3) or a backfill pressure of 146 kPa (21.2 psi) (Section 4.1.3) on the drip shield will be used.

6.3 INTERFACES WITH RELATED SYSTEMS

Interfaces with the emplacement drift invert are identified and evaluated below to determine sources of invert design loads and impacts on the emplacement drift invert configuration.

Emplacement Drift–The Emplacement Drift System structural support hardware (emplacement drift invert and waste package emplacement pallet) and performance enhancing barriers (invert ballast, drip shield, and backfill, if any) are interrelated as part of the Engineered Barrier System, (CRWMS M&O 2000e, p. 6). In this design, the waste package support pallet and drip shield rest directly on the emplacement drift invert. Ballast material is placed in the invert, between and around the carbon steel frame or under the steel tie and rail system. Backfill material, if used, will directly contact the emplacement drift invert structure between the outside of the drip shield and the drift wall, and will directly contact the drip shield that will transmit the backfill weight to the emplacement drift invert structure.

Ground Control–The Ground Control System interfaces with the Emplacement Drift System for material compatibility that conforms with post closure waste isolation performance requirements of the repository (CRWMS M&O 2000f, p. 6). The steel drift invert is not part of the ground control system, but is installed between the structural steel ground control components. The steel invert interfaces with the ground control in that the invert must be installed in a manner that avoids the structural steel set ground control components.

Waste Emplacement/Retrieval–The Waste Emplacement/Retrieval System interfaces with the Emplacement Drift System for waste package emplacement mode and hardware (CRWMS M&O 2000b, p. 7). With the side-lift gantry concept (CRWMS M&O 2000g, Section 7.0), where the waste package is lifted with the pallet, it is reasonable that the interface with the Waste Emplacement/Retrieval System would be the Emplacement Drift System waste package emplacement pallet, which is supported by the emplacement drift invert. The interface between the steel invert and the Emplacement Drift System is described above in the paragraph titled Emplacement Drift. The emplacement drift invert also interfaces with the Waste Emplacement/Retrieval System for the emplacement/retrieval gantry that is supported by the gantry rail.

Backfill Emplacement–The Backfill Emplacement System, if required, interfaces with the Subsurface Emplacement Transportation System for the transportation rails (CRWMS M&O 2000h, Volume I, p. 6). The emplacement drift invert interfaces with the Backfill Emplacement System at the gantry rail that supports the backfill equipment.

Subsurface Facility–The Subsurface Facility System interfaces with the Emplacement Drift System for the emplacement drift size and spacing (CRWMS M&O2000i, p. 7). The interface between the steel emplacement drift invert and the Emplacement Drift System is described above in the paragraph titled Emplacement Drift.

6.4 MATERIALS PROPOSED

6.4.1 Steel Material

Criterion for the emplacement drift invert requires structural members to be composed of carbon steel (Section 4.2.1.2) and Design Constraint 5.2.8 (CRWMS M&O 2000j) requires the invert along the bottom of the drifts to be constructed of a carbon steel frame with granular natural material used as ballast. Design concepts developed for the emplacement drift invert in *Invert Configuration and Drip Shield Interface* (CRWMS M&O 2000a) used steel materials conforming to ASTM A 572/A 572M for structural members (CRWMS M&O 2000a, Section 6.5). The steel material, covered by specification ASTM A 572/A 572M, is a high-strength low-alloy steel containing a carbon content varying from 0.21 to 0.26 percent depending on the grade of steel. Steel grades covered in ASTM A 572/A572M range from a minimum yield point of 290 MPa (42 ksi) (carbon 0.21 percent) to a maximum yield point of 450 MPa (65 ksi) (carbon 0.26 percent) (Section 4.1.1).

Carbon structural steel is covered by specification ASTM A 36/A 36M and has a yield point of 250 MPa (36 ksi) and a maximum carbon content of 0.26 percent. In contrast, stainless steel, covered by specification ASTM A 240/A 240M, has a minimum carbon content of 0.01 (yield point ranging from 275 MPa (40 ksi) to 415 MPa (60 ksi)) to a maximum carbon content of 0.15 (yield point ranging from 205 MPa (30 ksi) to 345 MPa (50 ksi)).

Other high-strength low-alloy steels that have enhanced atmospheric corrosion resistance are also available. These steels have better corrosion resistance than carbon structural steel (ASTM A 36/A 36M) and would generally be less expensive than stainless steel. Properties of suitable high-strength low-alloy steels are shown below for the specified grade where applicable (Section 4.1.1):

- ASTM A 242/A 242M, is a high-strength low-alloy structural steel (shapes, plates, and bars) with maximum carbon content of 0.15 percent, yield point of 345 MPa (50 ksi), and an atmospheric corrosion-resistance index of 6.0 or higher.

- ASTM A 588/A 588M, is a high-strength low-alloy structural steel (shapes, plates, and bars) with a maximum carbon content of 0.15 percent (Grade C), yield point of 345 MPa (50 ksi), and an atmospheric corrosion-resistance index of 6.0 or higher.

- ASTM A 709/A 709M, is a high-strength low-alloy structural steel (shapes, plates, and bars and quenched-and-tempered alloy structural steel plates for bridges) with a maximum carbon content for plate of 0.11 percent (Grade HPS 70W (HPS 485 W)), yield point of 485 MPa (70 ksi), and an atmospheric corrosion-resistance index of 6.0 or higher.

Determination of the atmospheric corrosion-resistance rate is discussed in ASTM G 101, Section 6.3. The determination of an atmospheric corrosion resistance index is based on the chemical composition of the steel materials. The higher the index, the more corrosion resistant is the steel.

Of the steel materials listed above the ASTM A 709/A 709M will be used in this technical report to evaluate the emplacement drift invert for reducing the amount of steel in the carbon steel frame. This structural steel material is weathering steel with an enhanced atmospheric corrosion resistance for use in bridges and has the lowest maximum carbon content (0.11 percent) and the highest yield point (485 MPa) compared with ASTM A 242/ A 242M and ASTM A 588/ A 588M steels. ASTM A 709/A 709M, Grade HPS 70W has a yield strength of 485 MPa (70 ksi) and is specified for plate to 100 mm (4 inches) thickness only. Steel shapes are not rolled in this grade of steel. Structural shapes for the invert frame will require fabrication from selected steel plate. Design evaluation of the drift invert frame is presented in Section 7.2. ASTM A 242/A 242M steel may be used for lighter weight steel frame members.

Use of ASTM A 709/A 709M steel will be satisfactory for the interface between the emplacement drift invert structure and the drip shields and the emplacement pallets. The drip shield is fabricated from titanium plates for long-term diversion of dripping water and long-term structural support, and feet (base angles) made of Alloy 22 to prevent direct contact between the titanium and the steel members of the invert to prevent possible hydrogen embrittlement of the titanium (CRWMS M&O 2000k, Section 6.1.1 and Sketch SK-0148 REV 05, pages II-1 and II-2). The emplacement pallet end beams are made of Alloy 22 plates to form the waste package supports that contact the invert structure and will be compatible with the ASTM A 709/A 709M steel (CRWMS M&O 2000k, Section 6.2.1 and Sketches SK-0144 REV 01 and SK-0189 REV 00, pages III-1 and III-2).

6.4.2 Ballast Material

Criterion for the emplacement drift invert requires ballast materials to be granular (Section 4.2.1.3) and Design Constraint 5.2.8 (CRWMS M&O 2000j) requires the ballast to be granular natural material. CPA 039 additionally assumes that the ballast be of crushed tuff (Section 4.3.2). Ballast materials are analyzed in Section 7.3.

7. INVERT DESIGN

7.1 DESIGN LOADS AND RELATED MATERIAL SELECTION

Emplacement drift invert design concepts developed in *Invert Configuration and Drip Shield Interface* (CRWMS M&O 2000a) are evaluated and analyzed in this section to determine material selection and feasibility for reducing the amount of steel materials in the concepts. Concepts proposed for the emplacement drift invert include a range of steel, from a heavy steel frame to a ballast only invert structure without the use of steel. Steel materials used for the modified steel invert with ballast, Figures 1 and 2 and the steel tie with ballast invert, Figures 3 and 4 are analyzed in Section 7.2. Ballast materials used for all of the invert concepts are analyzed in Section 7.3. The all-ballast invert is shown in Figures 5 and 6.

Design loads identified in Section 6.2 are quantified below and used to determine material properties of size, weight, and allowable stress for structural materials and bearing capacity of ballast materials required for the proposed emplacement drift invert concepts. Proposed concepts are analyzed and modified as needed to ensure optimum use of materials and design functionality.

7.1.1 Design Dead and Live Loads

The following dead loads, discussed in Sections 4.1.3 and 6.2, are defined below:

- Waste package/pallet assembly: Waste package, 85 MT (maximum) + Pallet, 3 MT = 88 MT (CRWMS M&O 2000g, Section 6.2).
- Drip shield: 4203 kg/(5.195+0.610)m = 724.03 kg/m (CRWMS M&O 2000k, Sketch SK-0148 REV 05, page II-1)
- Backfill (if used): Overton sand (Section 4.1.3), bulk density 1488 kg/m^3 (CRWMS M&O 2000d, Table 1).
- Waste emplacement/retrieval equipment: Gantry, 60 MT (CRWMS M&O 2000g, Section 6.3.4, page 53 of 77).
- Performance confirmation emplacement drift monitoring equipment: 148 MT maximum (Section 4.4.1).
- Backfill related emplacement equipment: 148 MT maximum (Section 4.4.1).

7.1.2 Seismic Loads

Seismic loads, discussed in Sections 4.4.2 and 6.2, are defined below:

- Subsurface horizontal motion of 0.242 g with a 1.5 multiplication factor, Section 4.4.2.

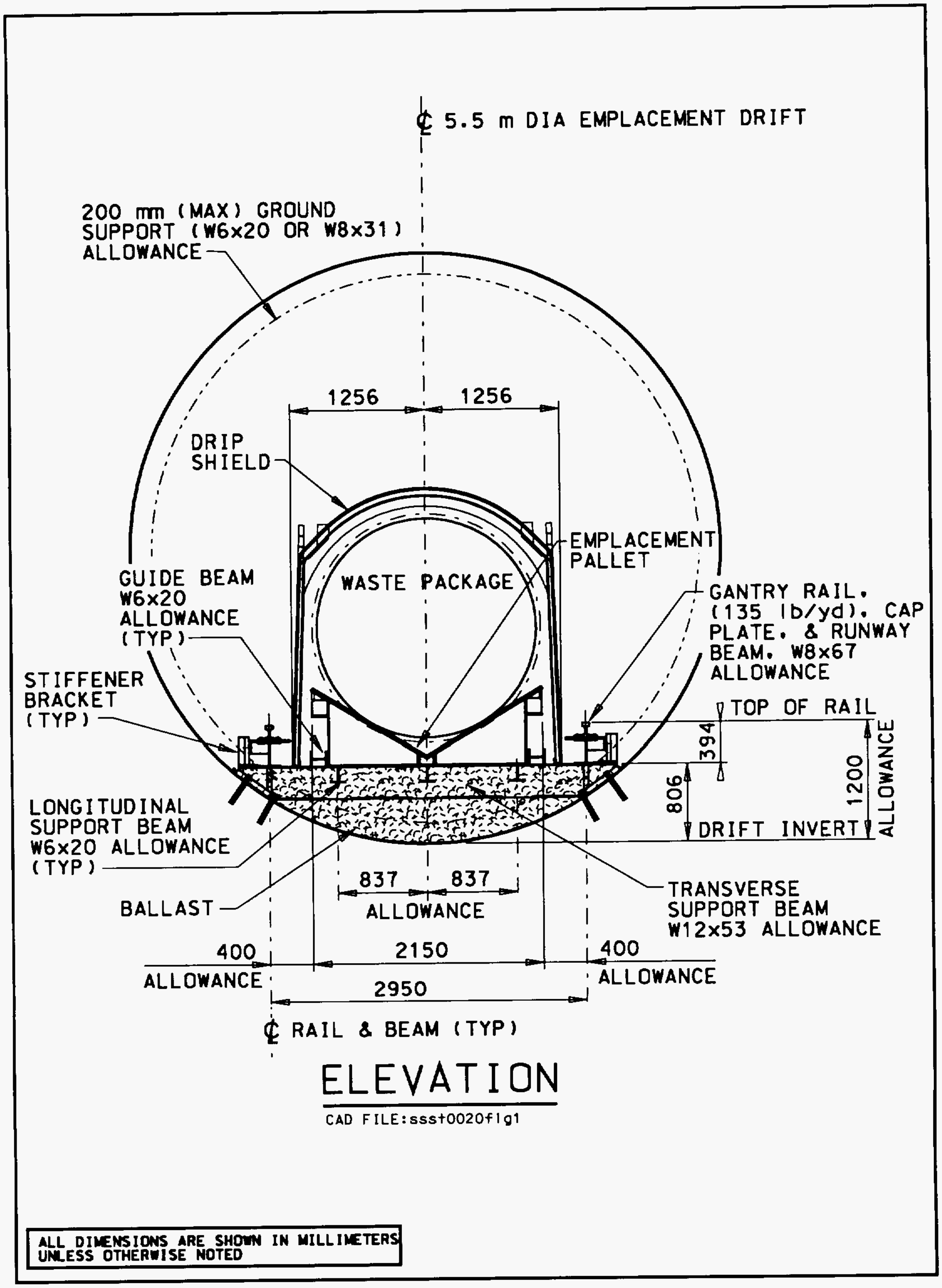

Figure 1. Steel Invert with Ballast - Elevation

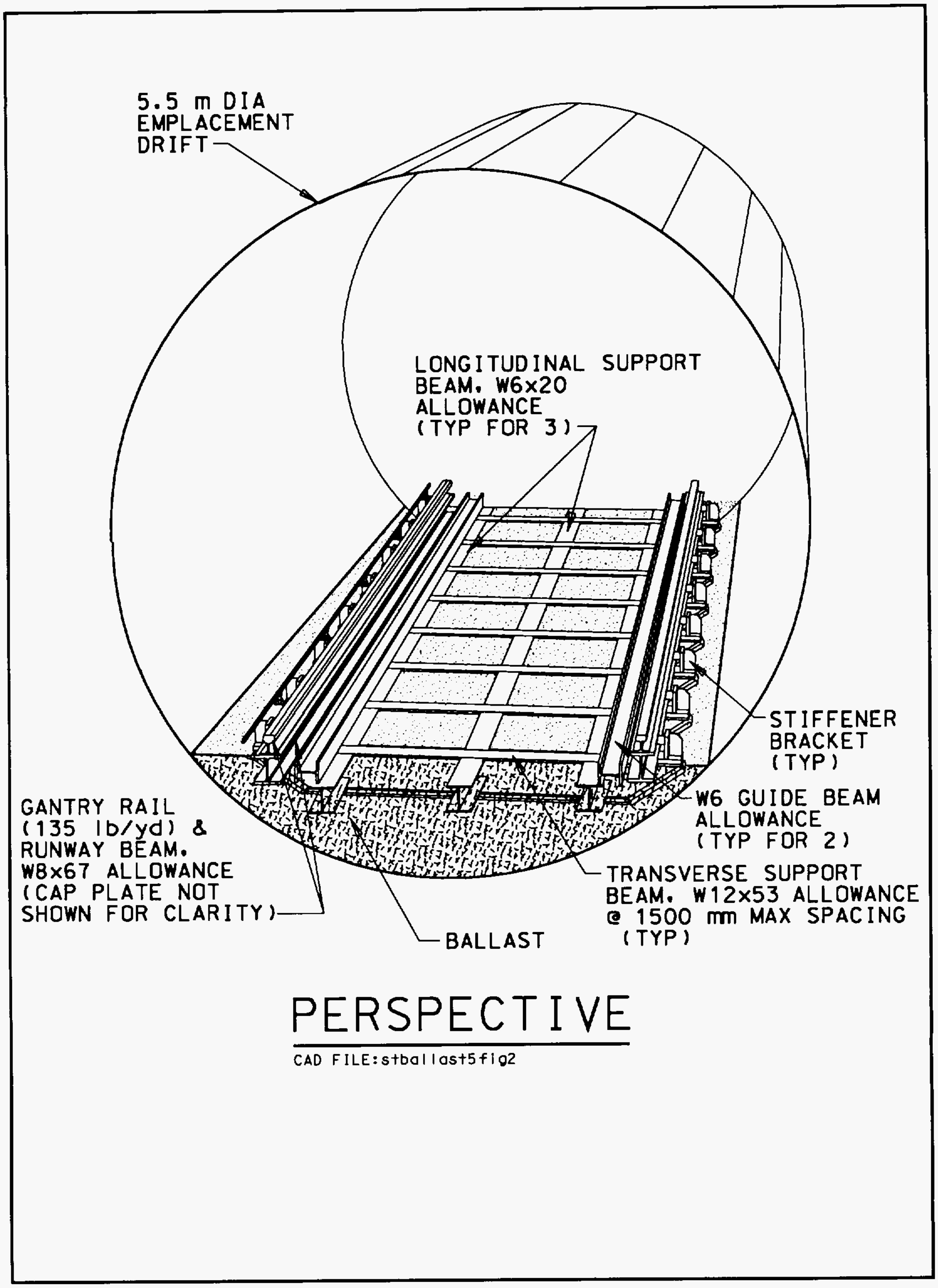

Figure 2. Steel Invert with Ballast - Perspective

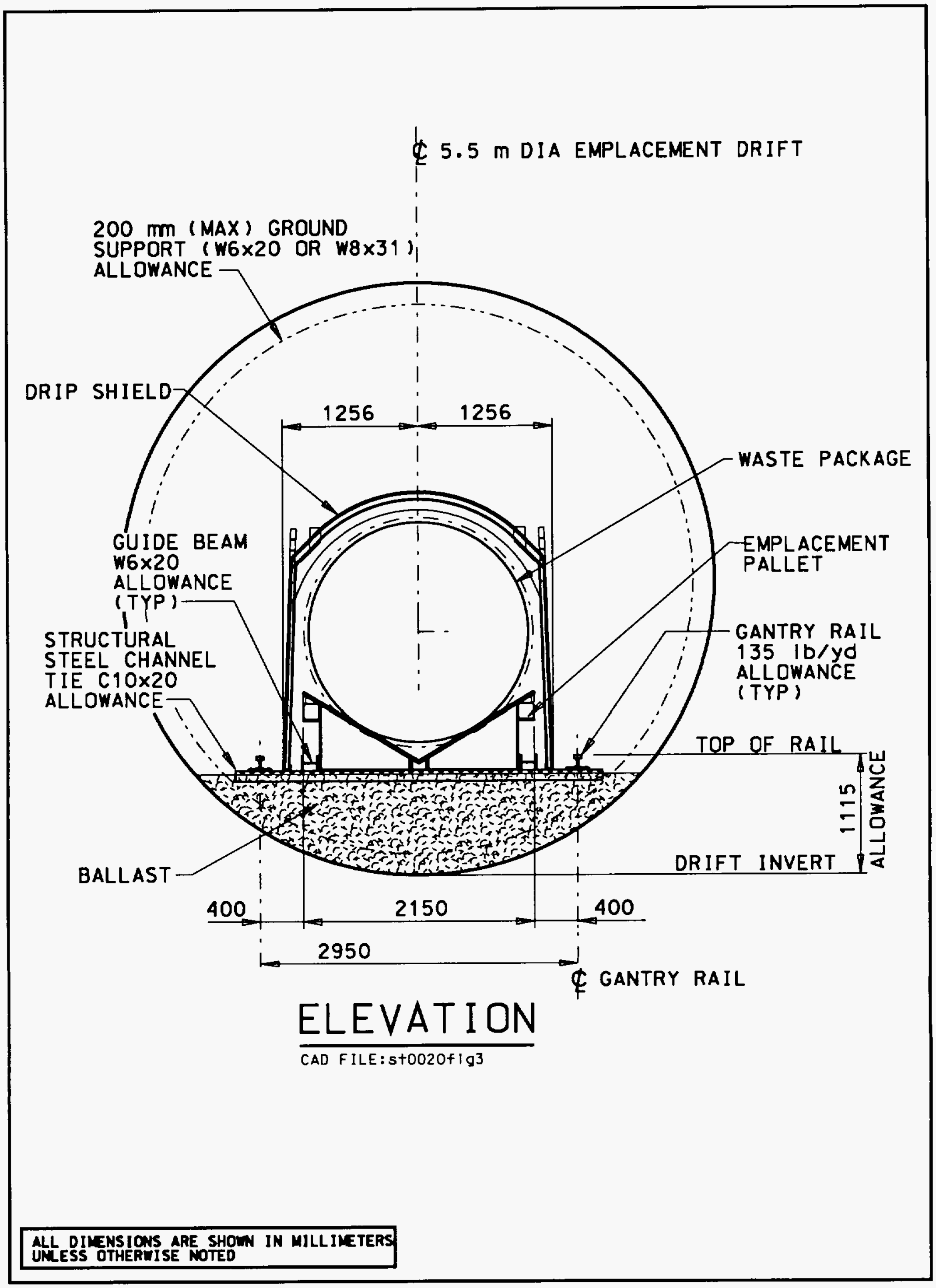

Figure 3. Steel Tie with Ballast Invert - Elevation

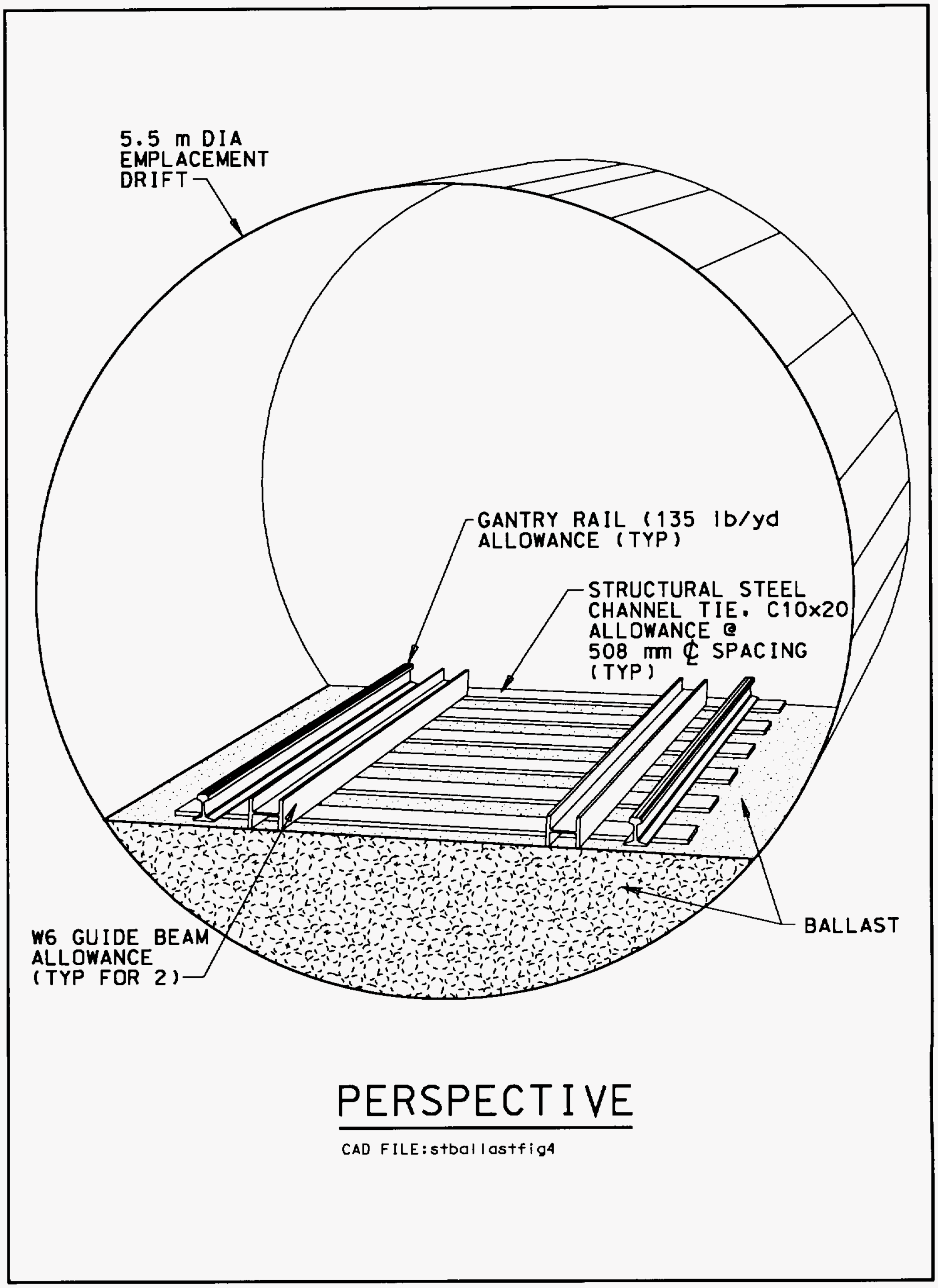

Figure 4. Steel Tie with Ballast Invert - Perspective

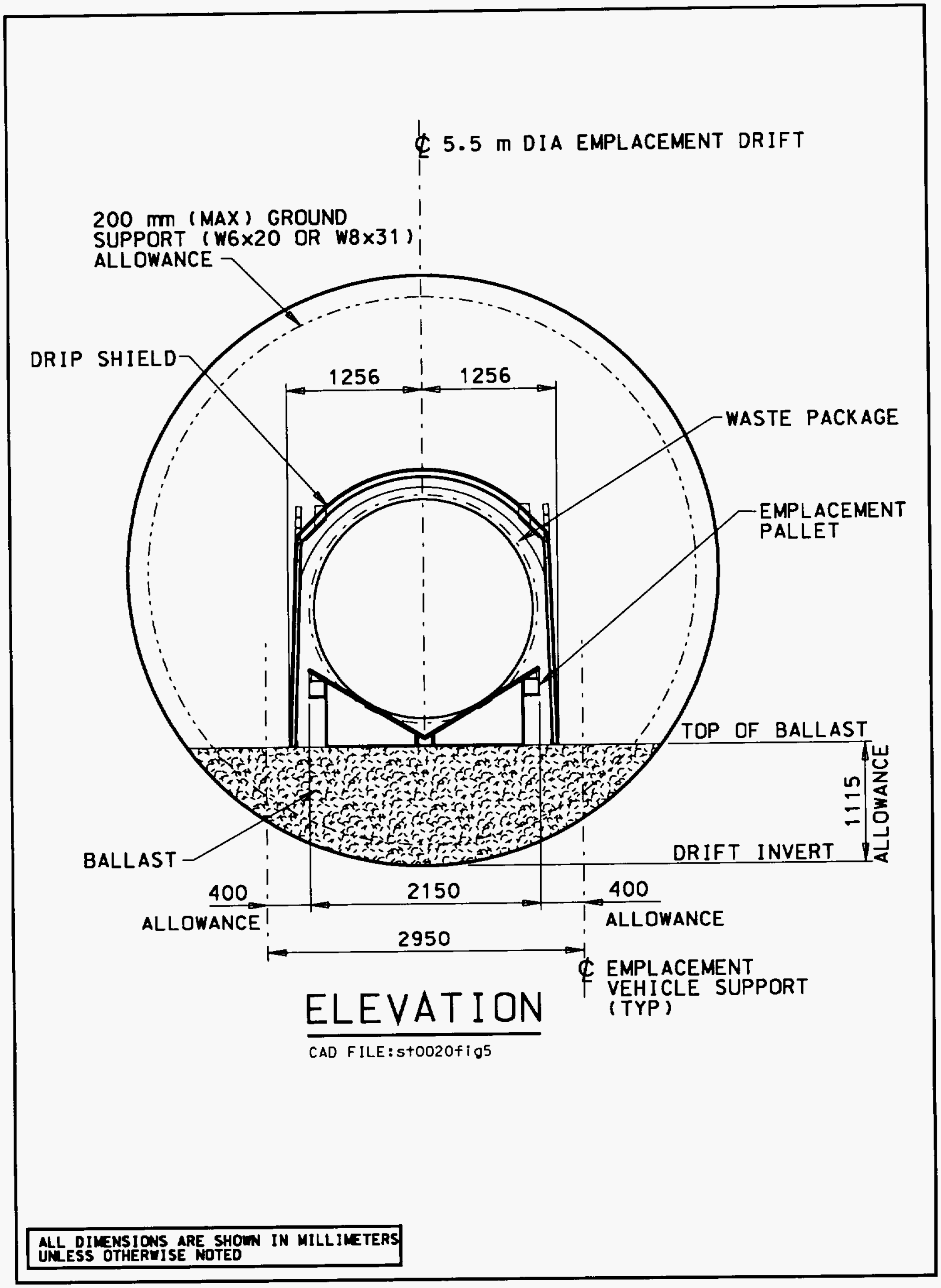

Figure 5. All-Ballast Invert - Elevation

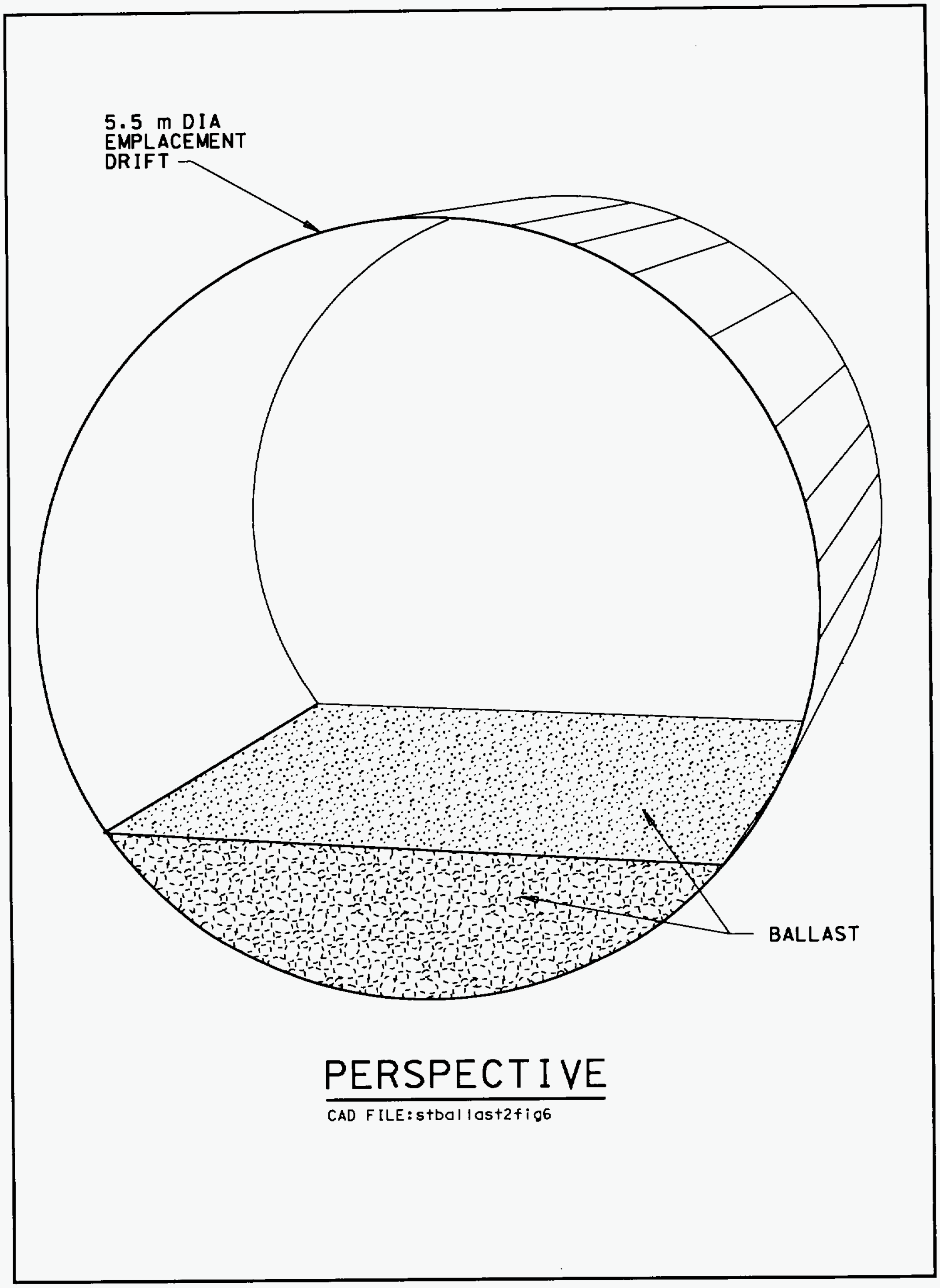

Figure 6. All-Ballast Invert - Perspective

- Subsurface vertical motion of 0.182 g with a 1.5 multiplication factor, Section 4.4.2.

7.2 DESIGN OF INVERT STRUCTURAL STEEL MEMBERS

Figures 1 and 2 show elevation and perspective views of the steel invert with ballast and Figures 3 and 4 show elevation and perspective views of the steel tie with ballast invert. Steel materials for these concepts from *Invert Configuration and Drip Shield Interface* (CRWMS M&O 2000a) were based on ASTM A 572/A 572M steel (CRWMS M&O 2000a, Section 6.5, p. 32). Steel member sizes for the transverse and crane runway beams were selected based on estimated allowances (CRWMS M&O 2000a, Section 6.4, p. 23) applied to the steel invert design in *Emplacement Drift Invert Structural Design Analysis* (CRWMS M&O 1998, Attachment I). Longitudinal and guide beams and channels for ties were based on estimated allowances.

Design of the transverse and crane runway beams in *Emplacement Drift Invert Structural Design Analysis* were based on a gantry load of 60 MT and a waste package load of 85 MT (CRWMS M&O 1998, Attachment I, p. I-27 of I-55). The combined gantry and waste package loads used equals 145 MT which is 3 MT less than the combined loads of the waste emplacement/retrieval gantry (60 MT) and the waste package/pallet assembly (88 MT) shown in Section 4.1.3. For the purpose of this report the 3 MT difference is not significant to the evaluation.

7.2.1 Steel Invert Frame

Maximum gantry support reactions (i.e., the emplacement gantry carrying a waste package) were developed (CRWMS M&O 1998, Attachment I, p. I-28 of I-55) and used to analyze the runway beam and the transfer (transverse) beam. The design of the crane runway beam was based on a span between the transverse beams of 1.22 meters (48 inches) and is conservative in flexural design with shear being the controlling design factor (CRWMS M&O 1998, Attachment I, p. I-29 of I-55). The current concept of the runway beam has a span of 1.5 meters (59 inches). This amounts to an increase in the span of approximately 25 percent. The combined stress ratio developed in CRWMS M&O 1998, Attachment I, p. I-33 of I-55 is 0.689. The compressive bending stress components of Equation H1-3 (AISC 1995, p. 5-54) are based, in this case, on the bending moment at mid-span of the runway beam. Applying the percentage of the increased span length to the combined stress ratio (1.25 x 0.689) yields a stress ratio of 0.861 that is still less than 1.0 and conforms to the AISC 1995 code. The increase in span between the transverse beams from 1.22 meters to 1.5 meters will not increase the runway beam size from a W8x67 with cap plate as shown in Figures 1 and 2. The runway beam size is not modified in this evaluation, thus maintaining the top of rail distance of 394 mm (CRWMS M&O 2000a, Figure 5) from the top of transverse beam.

The design of the transverse (transfer) beam (CRWMS M&O 1998, Attachment I, p. I-35 of I-55) is based on the loading transferred from the crane runway beam resulting from the emplacement gantry carrying a waste package. The waste package support assembly as proposed was to be a separate steel pier and "V"-shaped support that could be placed or designed to be placed directly on the invert of the drift (CRWMS M&O 1998, Section 7.1.4). This configuration of placement did not load the steel invert with the dead load of the waste package. The current concept of the waste package/pallet assembly in system performance criteria (Section 4.2.1.4) and the design of the pallet (CRWMS M&O 2000k, Section 6.2 and Sketch SK-0144, REV 01, page III-1) associated with the design constraint for line-loading with a minimum spacing of 10 cm between waste packages (Section 4.2.1.7) may load the transverse member directly with one-half of the waste package/pallet assembly weight of 88 MT (Section 4.1.3) (194 kips)/2 = 97 kips. This loading will add significant bending stress to the beam as currently designed. Additionally, the length of the transverse beam between load transfer centers has increased from 2.64 meters (104 inches) (CRWMS M&O 1998, Attachment I, p. I-36 of I-55) to 2.95 meters (116 inches) (CRWMS M&O 2000a, Figure 5). This amounts to an increase in the span of approximately 12 percent.

Design the transverse beam as a simple beam with the following loads:

-A uniform load totaling 97 kips distributed over a length of 1.8452 meters (6.05 feet), width of pallet base (CRWMS M&O 2000k, Section 6.2 and Sketch SK-0144, REV 01, page III-1), that is centered on the beam span of 2.95 meters (9.68 feet).

-A concentrated load from the drip shield weight of 4203 kg (9.27 kips), Section 4.1.3, supported by three transverse beams spaced as follows:

```
               5.485              Length of drip shield, meters
       ___________________________
             ↑#1     ↑      ↑
       |<   >|<   >|<   >|< >|   Spacing of transverse beams, meters
         1.5    1.5    1.5  0.985
```

Neglecting the width of the top flange of the transverse beam on the left and the related support of the beam, i.e., the drip shield just missed contacting the left transverse beam, the maximum weight of drip shield supported by beam #1, will be 1.5 meters (left of beam #1) + 0.75 meter (right of beam #1) or 2.25/5.485 (9.27 kips) = 3.8 kips. One-half of the supported drip shield weight, 1.9 kips, will be loaded on the transverse beam at a distance of 1256 mm (4.12 feet), Figure 1, each side of beam centerline or 0.72 foot (9.68 feet/2 – (4.12 feet)) from each beam end support.

-A concentrated load from the weight of potential backfill, contributed through the drip shield, and supported by three transverse beams spaced as shown above. The pressure on the drip shield from potential backfill is 146 kPa (21.2 psi), Section 4.1.3. The backfill load from the drip shield is 5485 mm (215.94 inches) by 2512 mm (98.9 inches) (CRWMS M&O 2000k, Sketch SK-0148, REV 05, page II-1) multiplied by the pressure of 21.2 psi or 215.94x98.9x21.2 = 452.8 kips. The maximum weight of potential backfill supported by beam #1, above, is 2.25/5.485(452.8 kips) = 185.6 kips. One-half of the backfill load, 92.8 kips, will be supported by the transverse beam at a distance of 0.72 feet from each beam support (see above). Backfill on each side of the drip shield and not supported directly by the drip shield, will be supported by the steel frame and ballast materials. This backfill load on the transverse beam will be negligible.

End reactions and maximum moment at the center of span are determined as follows:

Beam end reactions:

Distributed load = 97 kips/6.05 feet = 16.03 kips/foot

Concentrated loads = 1.9 + 92.8 = 94.7 kips

```
0.72 (Typ) |<>|                          94.7 kips (Typ)
           |  ↓     16.03 kips/foot     ↓
           ________↓↓↓↓↓↓↓↓↓↓↓↓↓↓________
           ↑ R1                          ↑ R2
           |< 1.82 >|<    6.05    >|< 1.81 >|
           |                                |
           |<           9.68 feet          >|
```

R1=R1a+R1b, R2=R2a+R2b, R1=R2

R1a=R2a=(16.03x6.05/2x9.68)(2x1.82+6.05)=5.01(9.69)=48.55 kips (AISC, p. 2-297) (Section 4.2.1.5)

R1b=R2b=94.7 kips (AISC, p. 2-298)

Maximum moment at center of span:

M1(max)=48.55(1.82+48.55/2x16.03)=48.55(3.33)=161.7 kip-feet (AISC, p. 2-297)

M2(max)=94.7(0.72)=68.2 kip-feet (AISC, p. 2-298)

M(max) at center of span=M1+M2= 161.7+68.2=229.9 kip-feet

Adding a vertical seismic acceleration of 0.182 g, Section 4.4.2 (TBD-241, TBV-273) and a multiplication factor of 1.5 (Section 4.4.2):

M (max) with seismic = 229.9+229.9(0.182x1.5)= 292.7 kip-feet; with 1/3 stress increase (AISC, Section A5.2, p. 5-30): 292.7x1/1.33=220.1 < 229.9 kip-feet, use 229.9 kip-feet

Beam selection is based on the elastic section modulus in the vertical direction (S)=Moment (M)/Bending stress (F_b) as follows:

F_b=0.60F_y (Specified minimum yield stress) (AISC, F1-5, p.5-46)

Compare beam selection using F_y = 50 ksi (ASTM A 572/A 572M, Section 4.1.1), F_b=30 ksi and F_y = 70 ksi (ASTM A 709/A 709M, Section 4.1.1) F_b=42 ksi.

S_{50}=M/ F_b=229.9x12/30 ksi=92.0 in^3 and S_{70}=M/ F_b=229.9x12/42 ksi=65.7 in^3

For S_{50}=92.0 in^3 use W18x55, S=98.3 in^3 (AISC, p. 1-23) [$76b_f/F_y^{1/2}$= $76(7.530)/50^{1/2}$=80.9 inches > lateral brace of 837 mm (33 inches) (Figure 1) (AISC, p. 5-46)] OK

For S_{70}=65.7 in^3 use W12x53, S=70.6 in^3 (AISC, p. 1-29) [$76b_f/F_y^{1/2}$= $76(9.995)/70^{1/2}$=90.8 inches (AISC, p. 5-46)] OK

Use W12x53 with ASTM A 709/A 709M steel, as discussed in Section 6.4.1, for the transverse beam.

The beam size determined for the transverse beam is less than the beam size allowance shown in CRWMS M&O 2000a, Figure 5 as a W12x65. The decrease in beam weight is approximately 18 percent.

As discussed above, the current concept of line loading the waste package/pallet assembly, if not loaded directly on the transverse beam, would alternatively be placed to bear on the three longitudinal beams. Such placement, at 10 cm, would load the three longitudinal beams with one half the weight of the waste package/pallet assembly.

For analysis purposes, in the design of the longitudinal beams, the one-half the weight of a waste package/pallet assembly 88 MT (194 kips)/2=97 kips will be distributed equally to each of the three longitudinal beams. One third of the waste package/pallet weight will be considered uniformly distributed on each longitudinal beam over the width of one pallet beam (CRWMS M&O 2000k, Sketch SK-0144, REV 01, page III-1), 552.4 mm (1.81 feet). The length of each longitudinal beam between transverse beam load centers is 1500 mm (4.92 feet) (CRWMS M&O 2000a, Figure 6).

Beam end reactions:

Distributed load = 97 kips/3 beams x 1.81 feet =17.86 kips/foot

```
               17.86 kips/foot
     ---------↓↓↓↓↓↓↓↓↓↓↓↓↓↓---------
     ↑ R1                           ↑ R2
     |< 1.56 >|<    1.81    >|< 1.55 >|
     |                                |
     |<           4.92 feet          >|
```

R1=R2=(17.86x1.81/2x4.92)(2x1.56+1.81)=3.28(4.93)=16.17 kips (AISC, p. 2-297)

Maximum moment at center of span:

M (max)=16.17(1.56+16.17/2x17.86)=16.17(2.01)=32.5 kip-feet

Adding a vertical seismic acceleration of 0.182 g, Section 4.4.2 (TBD-241, TBV 273) and a multiplication factor of 1.5 (Section 4.4.2):

M (max) with seismic = 32.5+32.5(0.182x1.5)= 41.4 kip-feet; with 1/3 stress increase (AISC, Section A5.2, p. 5-30): 41.4x1/1.33=31.1<32.5 kip feet, use 32.5 kip feet

Beam selection is based on the elastic section modulus in the vertical direction (S)=Moment (M)/Bending stress (F_b) as follows:

F_b=0.60F_y(Specified minimum yield stress) (AISC, F1-5, p.5-46)

Compare beam selection using F_y = 50 ksi (ASTM A 572/A 572M), F_b=30 ksi and F_y = 70 ksi (ASTM A 709/A 709M) F_b=42 ksi.

S_{50}=M/ F_b=32.5x12/30 ksi=13.0 in^3 and S_{70}=M/ F_b=32.5x12/42 ksi=9.3 in^3

For S_{50}=13.0 in^3 use W6x20, S=13.4 in^3 (AISC, p. 1-33) [$76b_f/F_y^{1/2}$= 76(6.02)/$50^{1/2}$=64.7 inches > beam span of 4.92 feet (59 inches) (AISC, p. 5-46)] OK

For S_{70}=9.3 in^3 use W6x20, S=13.4 in^3 (AISC, p. 1-33) [$76b_f/F_y^{1/2}$= 76(6.02)/$70^{1/2}$=54.7 inches<beam span of 59 inches (AISC, p. 5-46)], use W6x20 with F_y= 50 ksi

Use W6x20 with ASTM A 242/A 242M steel, as discussed in Section 6.4.1, for the longitudinal beam.

The beam size determined for the longitudinal beam is less than the beam size allowance of W12x65 in CRWMS M&O 2000a, Figure 5. The decrease in beam weight is approximately 69 percent.

Guide beams, W6x20 (CRWMS M&O 2000a, Figures 5 and 6) are provided to keep the waste package/pallet assembly aligned on the invert. The guide beam is loaded in the horizontal transverse direction by the horizontal seismic acceleration of 0.242 g (Section 4.4.2 (TBD-241, TBV-273)) acting on the waste package/pallet assembly positioned as discussed above. This horizontal loading will be applied to the guide beam as a uniformly distributed load over a distance equal to the width of a pallet beam (CRWMS M&O 2000k, Sketch SK-0144, REV 01, page III-1), 552.4 mm (1.81 feet). The length of each guide beam between the centerline of the transverse beams is 1500 mm (4.92 feet) (CRWMS M&O 2000a, Figure 6).

Beam end reactions:

Distributed seismic load = 97 kips(0.242)(1.5)/1.81 feet =19.45 kips/foot

```
              19.45 kips/foot
      ────────↓↓↓↓↓↓↓↓↓↓↓↓↓↓────────
↑ R1                                   ↑ R2
|< 1.56 >|<    1.81    >|< 1.55  >|
|                                  |
|<            4.92 feet           >|
```

R1=R2=(19.45x1.81/2x4.92)(2x1.56+1.81)=3.58(4.93)=17.65 kips (AISC, p. 2-297)

Maximum moment at center of span:

M (max)=17.65(1.56+17.65/2x19.45)=17.65(2.01)=35.54 kip-feet, with 1/3 stress increase (AISC, Section A5.2, p. 5-30): 35.54x1/1.33=26.72 kip feet

Beam selection is based on the elastic section modulus in the vertical direction (S)=Moment (M)/Bending stress (F_b) as follows:

F_b=0.60F_y(Specified minimum yield stress) (AISC, F1-5, p.5-46)

Compare beam selection using F_y = 50 ksi (ASTM A 572/A 572M), F_b=30 ksi and F_y = 70 ksi (ASTM A 709/A 709M) F_b=42 ksi.

S_{50}=M/ F_b=26.72x12/30 ksi=10.7 in^3 and S_{70}=M/ F_b=26.72x12/42 ksi=7.6 in^3

For S_{50}=10.7 in^3 use W6x20, S=13.4 in^3 (AISC, p. 1-33) [76b_f/$F_y^{1/2}$= 76(6.02)/50$^{1/2}$=64.7 inches > beam span of 4.92 feet (59 inches) (AISC, p. 5-46)] OK

For S_{70}=7.6 in^3 use W6x20, S=13.4 in^3 (AISC, p. 1-33) [76b_f/$F_y^{1/2}$= 76(6.02)/70$^{1/2}$=54.7 inches<beam span of 59 inches (AISC, p. 5-46)] use W6x20 with F_y= 50 ksi

Use W6x20 with ASTM A 242/A 242M steel, as discussed in Section 6.4.1, for the guide beam.

The beam size determined above for the guide beam is the same as the beam size allowance of W6x20 in CRWMS M&O 2000a, Figure 5. There is no increase in beam weight.

Miscellaneous steel materials for rails, base plates, stiffener plates and brackets, connections, bolts, nuts, and washers are not part of this evaluation.

7.2.2 Steel Tie

C9x20 channels were proposed for the steel ties in CRWMS M&O 2000a, Figures 7 and 8. Bearing pressures under the steel ties are determined in Section 7.3.3.2. Tables 1 and 2 show average ballast pressures under one and two ties, respectively, loaded with a single waste package/pallet assembly and without loads from the drip shield and backfill. *Tables 3 and 4* show pressures as in Tables 1 and 2, but with loads from the drip shield and backfill. With a spacing of 508 mm (20 inches) between centerline of ties the maximum load will be from a pallet beam resting directly on a single tie. The tables show lower pressures with the use of a C10x20. Lower pressures can also be achieved with the use of C12x20.7 that would not cause a significant increase in the amount of steel material.

The steel tie is generally uniformly supported by the ballast materials in the region of loading. Gantry loads and waste package/pallet loads applied to the steel tie are distributed through the steel to the ballast materials. The gantry and waste package/pallet loads are applied and distributed locally to the tie with the possibility that some bending may occur in the tie due to deflection. This condition will be analyzed in future work.

7.3 DESIGN OF INVERT BALLAST MATERIAL

For the steel tie with ballast invert configuration, Figures 3 and 4, the gantry rails carrying WP/pallet assembly will be supported on steel ties that will be supported on the crushed rock ballast in a manner similar to the rail support provided for railroad trains. After emplacement, WP/pallet assembly will be supported on steel ties directly supported by the crushed rock ballast. There is one alternative of this configuration, in which the WP/pallet will be supported by rock ballast without steel ties and rails. In this section, evaluation of proposed ballast materials for the invert, properties of invert ballast, bearing capacity of rock ballast, proper compaction, ballast thickness, and constructibility of crushed tuff (CPA 039, Section 4.3.2) as invert ballast are discussed.

7.3.1 Ballast Material

The proposed ballast material for the emplacement drift invert is the crushed welded tuff from the tunnel boring machine (TBM) muck (cuttings) at Yucca Mountain. Among the TBM cuttings, the Topopah Spring welded tuff (TSw2) is currently being considered as the ballast material. Other rock materials allowed for consideration in the past were limestone and marble. Final material selection requires additional testing of thermal, chemical, and hydrologic properties of candidate materials, which are beyond the scope of this study.

7.3.2 Properties of Crushed Rock Ballast

For the invert configuration in this study, the crushed rock ballast must serve as a structural bearing material. In order for it to meet this function it must have the proper quality and gradation. For railway track construction, a variety of most common materials for railroad ballast, which include limestone, granite, quartzite, etc., and the recommended qualities and gradations have been listed in the *Manual for Railway Engineering* (AREA 1997, Vol. 1, pp. 1-2-9 to 1-2-13). However, it should be noted that the specification does not limit the use of any rock type which can be processed into ballast when the material is properly defined and tested in accordance with the specifications (AREA 1997, p. 1-2-16). Therefore, crushed tuff, which is currently proposed as rock ballast for the invert material (CPA 039, Section 4.3.2), should be considered suitable as long as its properties meet the intended function and be tested in accordance with the specifications.

Proper Quality-The crushed rock structural ballast must be strong and durable. Recommendation for these attributes and the testing specifications according to the *Manual for*

Railway Engineering (AREA 1997, p. 1-2-12, Table 2-1) (Section 4.1.2) for limestone as a representative is given in the following:

• Bulk Specific Gravity:	2.60 min. (ASTM C 127)
• Absorption Percent:	2.0 max. (ASTM C 127)
• Clay Lumps and Friable Particles:	0.5% max. (ASTM C 142)
• Degradation:	30% max. (see Note 1 below)
• Soundness (Sodium Sulfate) 5 Cycles:	5.0% max. (ASTM C 88)
• Flat and/or Elongated Particles:	5.0% max. (ASTM D 4791)
• Percent Material Passing No. 200 Sieve:	1.0% max. (ASTM C 117)

Note 1: Materials having gradations containing particles retained on the 1 inch sieve shall be tested by ASTM C 535. Materials having gradations with 100% passing the 1 inch sieve shall be tested by ASTM C 131.

It should be noted that the above recommended values are for the conventional railway ballast conditions. For the current invert ballast design for emplacement drift, the specification should be intended as a guideline because it may not cover all of the requirements and conditions for the emplacement drift invert. For example, the limiting maximum value of degradation may need to be reduced to provide further resistance. The reason is that one major source of ballast fines is aggregate degradation under trafficking (Barksdale 1991, p. 11-7), i.e., aggregate breakdown under repeated traffic loading, which is additional to the original fines in the ballast. However, the percentage of fines (i.e., passing No. 200 sieve) must be kept with a maximum of 1% during the preclosure period to ensure free water drainage. Therefore, the final limiting values for the proper quality should be determined based on the tests incorporating field factors that represent the actual in-track performance of the ballast material at the emplacement drift conditions.

Proper Gradation-The recommended gradations for ballast materials in the *Manual for Railway Engineering* (AREA 1997, Vol. 1, p. 1-2-13, Table 2-2) may not be suitable for the current emplacement drift invert if the ballast is considered as the supporting materials for the waste package assembly. The reason is that the conventional railway ballast materials have a uniform gradation instead of well-graded particles, which is good for drainage but may not be strong enough for supporting the heavy waste package assembly for such a long period. Moreover, the emplacement drift invert will be in relatively dry condition during the preclosure period, hence, the drainage is not a major concern. Therefore, it is proposed that the crushed tuff with a well-graded particles ranging from 2 inches to No. 200 sieve size (with 1% as maximum) is preliminarily considered to be adequate. This will allow free-liquid-phase water to drain out of emplacement drifts, via the emplacement drift floor (Section 4.2.1.1 (TBV-284)) and will not prevent water entering the emplacement drifts from draining directly into the surrounding host rock without draining along the drift, for collection in a centralized location (Section 4.3.1, CPA 026). Notice that this gradation is a little different from that of the conventional railway ballast materials, which usually have a uniform gradation and permit little, if any, minus No. 4 sieve materials to be present (Barksdale 1991, p. 11-7). However, the major concern for the property of ballast in emplacement drift invert is high bearing capacity rather than water drainage. A well graded aggregate (or ballast) gives the maximum density when compacted, which in turn will achieve higher bearing capacity. It needs to be pointed out that the final gradation will not be known until proper tests are conducted for ballast under emplacement invert drift conditions.

7.3.3 Bearing Capacity of Crushed Tuff Ballast

High bearing capacity is one of the major key factors to ensure satisfactory ballast performance at emplacement drift invert. In order to be suitable for emplacement drift invert construction, TBM muck from TSw2 formation at Yucca Mountain must possess sufficient strength to prevent any bearing capacity (BC) failure.

In order to determine whether the crushed tuff has adequate bearing capacity, it is essential to determine the loading (i.e., pressure) exerted on the ballast under two different scenarios: (1) ballast under ties via rails, which are subjected to the wheel loading of gantry carrying WP/pallet assembly, and (2) ballast directly supports WP/pallet with or without ties in between.

7.3.3.1 Average Ballast Pressure – Scenario 1

In this scenario, the pressure exerted on the ballast is due to the wheel loading of gantry carrying the WP/pallet with a transportation speed V. The average ballast pressure (ABP) at the tie face can be calculated by the following equation (AREA 1997, Vol. 1, p. 1-2-21):

$$ABP = [2P(1+IF/100)(DF/100)]/A \quad \text{(in psi)} \qquad \text{(Eq. 1)}$$

where:

P = Wheel loading in lbs
IF = Impact factor for track in percent = 33V/100D
DF = Distribution factor in percent
A = Contact area of tie = B x L
V = transportation speed in miles per hour
D = Diameter of wheel in inches
B = Tie width in inches
L = Tie length in inches

The distribution factor in the above equation is the percentage of load distributed to each tie either side of the applied wheel load. This factor varies depending on the train or gantry wheel design, wheel load, tie spacing, and track condition. The actual values cannot be determined without further study and proper testing. In this study, the distribution factor will vary from 40 to 50 percent. It should also be noted that in order to apply this equation properly to this study the whole length of tie will not be used in the calculation because the distance between gantry rails is almost twice as much of normal rail gage. For this analysis, a distance of 5 ft. of tie under the rail will be used in the equation. Figure 7 shows the average ballast pressure vs. various distribution factors at ties, which are steel channels C 9x20 and C 10x20. The values used in the calculation are: P = 40793 lbs (i.e., 148 MT/8 wheels x 2205 lbs/MT) (CRWMS M&O 1997, Figure 7.4.2), V = 1.7 mph (CRWMS M&O 2000g, Section 6.5), D = 40 cm = 15.7 in. (CRWMS M&O 2000g, Section 6.5), B = 9 and 10 in., L = 1.52 m (i.e., 5 ft, or 60 in.). Note that each WP/pallet weighs 88 MT and each gantry weighs 60 MT and has eight wheels. Each gantry carrying WP/pallet travels with a maximum speed of 1.7 mph (CRWMS M&O 2000g, Section 6.5). See detailed calculations of ballast pressure in Section 7.3.7.

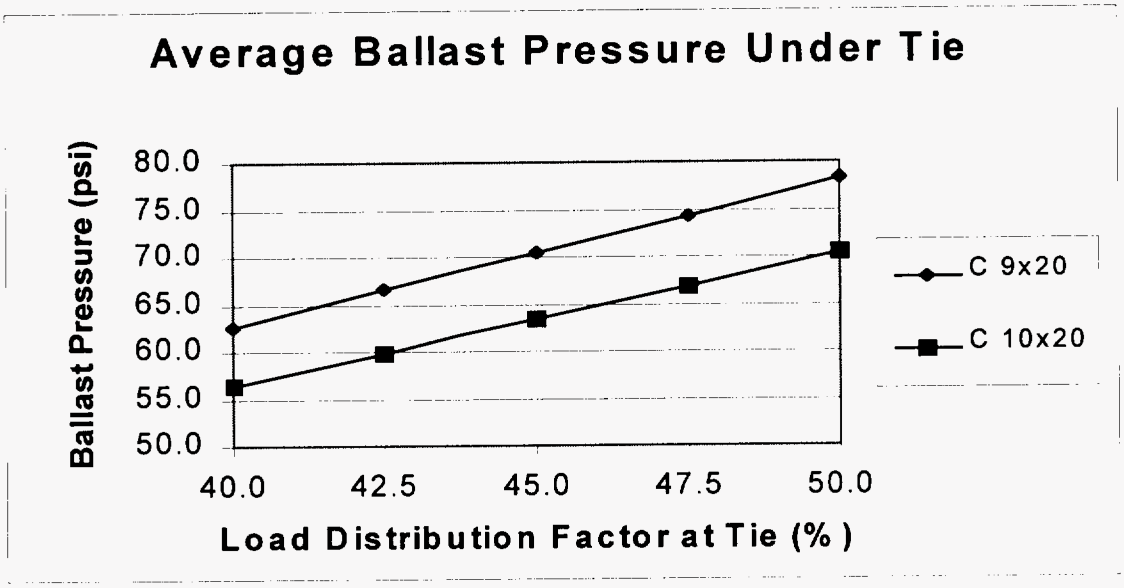

Figure 7. Average Ballast Pressure Under Steel Tie Subjected to Wheel Loading of Gantry Carrying WP/Pallet

The following points can be summarized regarding the ballast pressures under ties subjected to wheel loading on rails:

- The ballast pressure increases with wheel load and gantry speed and decreases with increased tie area. Therefore, it is feasible to design the gantry track system so that the average ballast pressure can be smaller than the allowable bearing capacity of the ballast.
- For the steel tie of C 9x20, the average ballast pressures range from 63 to 78 psi based on the load distribution factors of 40 to 50 percent.
- For the steel tie of C 10x20, the average ballast pressures range from 56 to 70 psi based on the load distribution factors of 40 to 50 percent.
- The load distribution factor varies depending on the train or gantry wheel design, wheel loading, tie spacing, and track condition. In the calculation, load distribution factors vary from 40 to 50 percent. However, the actual values may be smaller than these values, which will result in lower pressures on the ballast. Therefore, it is very important to determine the actual value with further study and proper testing.
- The tie length used in calculating the average ballast pressure is 5 ft, which is similar to the regular rail gage distance. Since the rail gage distance in this study is twice as much of this value, further study is needed to determine the actual stress distribution under the tie.

7.3.3.2 Average Ballast Pressure – Scenario 2

In this scenario, the WP/pallet assembly is directly supported by compacted rock ballast with or without ties in between.

Case 1 – WP/pallet supported by ballast through ties

(a) Without drip shield and backfill

The maximum weight of each WP/pallet assembly is 88 MT (CRWMS M&O 2000g, Section 6.2), half of this weight, i.e., 44 MT, will be supported by ties through the contact area of each pallet. The bottom area of each pallet beam is 1845.2 (across the drift) x 552.4 (along the drift) mm (see Attachment III, p. III-1 of CRWMS M&O 2000k). It should be noted that the final tie spacing is not determined yet. For most railway track construction, it is about 20 to 25 inches (508 to 635 mm). For the emplacement drift invert design, the tie spacing may be selected to be smaller than 20 inches in order to have smaller load distribution factor. Therefore, based on the above dimensions, each pallet beam may be supported by more than one tie. For conservative design, the maximum load will be supported by one tie. It should also be noted that the above mentioned weights are only for static condition. In order to consider the effect of seismic force, the weights due to static loading should be multiplied by a factor of (1 + 0.182x1.5), in which 0.182 is a maximum underground vertical acceleration and 1.5 is a factor to account for seismic force to equivalent static loading (see Section 4.4.2). Tables 1 and 2 show the average ballast pressure under ties for different tie dimensions. Note that the ABP is derived by dividing the total weight including seismic force by the tie contact area.

Table 1. Average Ballast Pressure (psi) Under One Tie Subjected to WP/Pallet Assembly Weight

	L = 3.6 m	L = 3.8 m	L = 4.0 m	L = 4.2 m
C 9x20	96.8	91.8	87.1	83.0
C 10x20	87.1	82.6	78.4	74.7

Table 2. Average Ballast Pressure (psi) Under Two Ties Subjected to WP/Pallet Assembly Weight

	L = 3.6 m	L = 3.8 m	L = 4.0 m	L = 4.2 m
C 9x20	48.4	45.9	43.6	41.5
C 10x20	43.6	41.3	39.2	37.3

(b) With drip shield and backfill

Under this situation, the additional loads from the backfill bearing on the drip shield and the drip shield of 462.07 kips (i.e., 452.8+9.27, see Section 7.2.1) will be applied to the ties. For each drip shield with a length of 5.485 m (215.94 in.) (see Section 7.2.1), there will be 10.8 ties under the drip shield with a tie spacing of 20 in. Using rounded values of 10.8 ties, i.e., 11 ties, each tie will be subjected to an additional load of 42 kips (462.07/11 = 42). By using the same calculation method as in case (a), the average ballast pressure under one and two ties subjected to the weight of the WP/pallet assembly, the drip shield, and the backfill are shown in Tables 3 and 4.

Table 3. Average Ballast Pressure (psi) Under One Tie Subjected to Weight of WP/Pallet Assembly, Drip Shield and Backfill

	L = 3.6 m	L = 3.8 m	L = 4.0 m	L = 4.2 m
C 9x20	138.7	131.4	124.9	118.9
C 10x20	124.9	118.3	112.4	107.0

Table 4. Average Ballast Pressure (psi) Under Two Ties Subjected to Weight of WP/Pallet Assembly, Drip Shield and Backfill

	L = 3.6 m	L = 3.8 m	L = 4.0 m	L = 4.2 m
C 9x20	90.3	85.6	81.3	77.4
C 10x20	81.3	77.0	73.2	69.7

Case 2 – WP/pallet directly supported by ballast

For this case, the WP/pallet assembly will be directly supported by the compacted tuff ballast. The total weight of each WP/pallet assembly will be distributed to two pallet beams under each WP/pallet assembly. Based on a maximum weight of 56 (i.e., 44x(1+0.182x1.5)) MT for half of the WP/pallet assembly and the bottom bearing area of the pallet beam, i.e., 1845.2 x 552.4 mm, the average ballast pressure is calculated to be 78.2 psi.

Case 3 – Drip shield and Backfill directly supported by ballast

For this case, the weight of the drip shield and backfill will be directly supported by the compacted tuff ballast. The total weight of each drip shield plus backfill will be distributed to two contact areas from the drip shield legs or sides. The contact area of each drip shield leg will support one-half the weight of the drip shield plus backfill, which is 231 kips (i.e., 462/2 rounded off). Based on the contact area of 647.8 in^2 (i.e., 215.94x3), the average ballast pressure is calculated to be 356.7 psi.

Based on the above calculations, the average ballast pressure for WP/pallet assembly placed on the ballast with or without ties can be summarized as follows:

- The average pressures of ballast under the drip shield legs due to the weight of the drip shield and backfill is the highest, followed by the case of one tie subjected to the WP/pallet, drip shield and backfill. The average pressures of ballast under two ties subjected to WP/pallet assembly are the lowest, with their magnitudes one half of the case for one tie.

- The average ballast pressures for ties subjected to loading due to the backfill and drip shield increase about 43 % for one tie and about 86 % for two ties than those without considering backfill and drip shield.

- It is pointed out that the ballast pressure under the drip shield legs subjected to the weight of drip shield and backfill is very high, i.e., 356.7 psi. The major reason for this high pressure is the very narrow width of the base angles on the drip shield legs, which is 75 mm (3 inches)

(CRWMS M&O 2000k, Sketch SK-0148, REV 05, page II-2). These base angles require analysis to determine if they can be widened to better distribute the bearing load.

7.3.3.3 Estimated Bearing Capacity of Crushed Tuff Ballast

Bearing capacity is the ability of soil to safely carry the pressure placed on the soil from any engineered structure without undergoing a shear failure with accompanying large settlement (ASCE 1993, Section 1-2, p. 1). In this section, the bearing capacity of the compacted crushed tuff under the steel ties and directly under WP/pallet will be estimated.

For cohesionless soils (i.e., crushed tuff in this study) without overburden, the ultimate bearing capacity, q_0, can be shown as (Winterkorn and Fang, 1975, pp. 126-129):

$$q_0 = \frac{1}{2}\gamma B N_\gamma \zeta \qquad \text{(Eq. 2)}$$

where:

γ = unit weight of compacted crushed tuff
B = width of steel tie or pallet
N_γ = dimensionless factor related to angle of internal friction of soil
ζ = dimensional shape factor = 1 – 0.4B/L
L = length of steel tie or pallet

Currently, there is no test data available for angle of internal friction of compacted crushed tuff with the gradation specified in Sec. 7.3.2. However, for well compacted cohesionless material, an important criterion can be used to evaluate its compaction characteristics, i.e., relative density. For a densely compacted sand, the relative density is in the range of 2/3 to 1 (Winterkorn and Fang, 1975, p. 256). Since the crushed tuff to be used as ballast will be highly compacted and well-graded, it is reasonable to assign the value of relative density with a minimum value of 70 percent. For relative density of 70 percent, the angle of internal friction is about 43° for coarse to fine sand with some gravel (see Figure 7.26 of Winterkorn and Fang, 1975, p. 263). To be conservative, an angle of internal friction of 40° is used for this study. The N_γ value for an angle of internal friction of 40° is 109.41 (based on Table 3.1 of Winterkorn and Fang, 1975, p. 127). It should be noted that the actual data for the unit weight of highly compacted and well-graded crushed tuff is not available, which needs to be obtained by further testing. For the purpose of this study, results obtained from Table 8.4 of a technical report titled *Construction Applications for TSw2 TBM Cuttings at Yucca Mountain* (Gertsch et al. 1993, p. 50) are used, in which the maximum dry unit weight and optimum water content of the TBM cuttings based on modified Proctor test are 116.7 lb/ft^3 and 13.7%, respectively. The unit weight for this moisture content is calculated to be 133 lb/ft^3. It is reasonable to use 90% of the latter, i.e., 120 lb/ft^3, as the unit weight for the compacted crushed tuff for estimating the bearing capacity.

Therefore, by substituting γ = 120 lb/ft^3, N_γ = 109.41, B = 9 and 10 in., and L = 3.6 to 4.2 m into Eq. 2, the ultimate bearing capacity for tuff ballast under tie is shown in Table 5. For cohesionless soil, the factor of safety is 2 (ASCE 1993, p. 36). Using a factor of safety of 2 the allowable bearing capacity for tuff ballast under steel tie is shown in Table 6. In the same way, by substituting the same γ and N_γ values and B =552.4 mm, and L = 1845.2 mm into Eq. 2, the ultimate and allowable bearing capacities of tuff ballast under WP pallet are calculated to be 72.7 and 36.4 psi, respectively.

Table 5. Ultimate Bearing Capacity of Tuff Ballast (psi) Under Steel Tie

	L = 3.6 m	L = 3.8 m	L = 4.0 m	L = 4.2 m
C 9x20	33.3	33.4	33.4	33.4
C 10x20	36.9	37.0	37.0	37.1

Table 6. Allowable Bearing Capacity of Tuff Ballast (psi) Under Steel Tie

	L = 3.6 m	L = 3.8 m	L = 4.0 m	L = 4.2 m
C 9x20	16.7	16.7	16.7	16.7
C 10x20	18.5	18.5	18.5	18.5

It should be noted that the allowable bearing capacity calculated based on Eq. 2 is conservative, or on the lower bound. The reason is that Equation 2 is mainly for the homogeneous soil materials with larger thickness. For the current emplacement drift invert configuration (see Figure 3), the ballast thickness is quite shallow with a maximum thickness less than 1 m at center of the drift and zero at the edge of invert. Since the subgrade (i.e., bedrock in this study) underlying the ballast is of TSw2, which is much stronger rock than the crushed tuff, the actual bearing capacity should be greater than that calculated based on the crushed tuff alone. Furthermore, the compacted crushed tuff is not completely cohesionless, instead, it should have some cohesion due to the interlocking of the particles after compaction. Therefore, the bearing capacity will be greater if cohesion is considered. Moreover, an allowable bearing pressure of 8 to 10 tons/ft^2 (i.e., 111 to 139 psi) are shown for materials with more than 10% gravel and well graded gravel soils (Merrit, et al, eds. 1996, p. 7.27). For conservative design, a nominal value of 111 psi is used as the upper bound of the allowable bearing capacity in this study.

7.3.3.4 Evaluation of Bearing Capacity of Tuff Ballast

Based on the discussions in Sections 7.3.3.1 through 7.3.3.3, the relationships between ballast pressures and allowable bearing capacities are shown in Figures 8 through 13 for the following cases: steel tie C 9x20 under moving gantry with WP/pallet, steel tie C 10x20 under moving gantry with WP/pallet, steel tie C 9x20 directly supporting WP/pallet with and without backfill, and steel tie C 10x20 directly supporting WP/pallet with and without backfill, respectively. The following conclusions can be made regarding the evaluation of bearing capacity of crushed tuff as rock ballast for the emplacement drift invert:

- By comparing the magnitudes of pressure exerted on ballast and the bearing capacity of ballast under ties or WP/pallet, the calculated allowable bearing capacity of crushed tuff ballast based on Eq. 2 for cohesionless material is the lowest, which is lower than the average ballast pressure under loading of the moving gantry carrying a WP/pallet.

- In order to prevent the bearing capacity failure for ties under gantry wheel loading, it is desirable to increase the bearing area by increasing the width or length of the tie, or to decrease the tie spacing so that the load distribution factor could be reduced, thereby the pressure can be reduced.

- By comparing the results in Tables 1 and 2, it can be clearly seen that the pressure under the tie will be much smaller if two ties can be placed under each pallet. This can be achieved either by reducing the tie spacing or increase the dimension of the longitudinal (i.e., parallel to axis of drift) side of the pallet.

- By comparing the results in Tables 1 and 2 with those in Tables 3 and 4, it indicates that the average ballast pressures for the case with backfill and drip shield increase about 43 percent for one tie and 86 percent for two ties from those without backfill and drip shield.

- The difference between calculated allowable bearing capacities (lower bond) and the nominal allowable bearing capacity (upper bound) is quite large. If using the lower bound value, the bearing capacity failure is almost unavoidable unless further research in track behavior is conducted to reduce the load distribution factor (such as reducing tie spacing, etc.) or increase the tie dimension. On the other hand, if the upper bound value is used, there will be no bearing capacity failure except for the cases when one tie is subjected to WP/pallet assembly with drip shield and backfill (excluding the case of the C 10x20 at a length of 4.2 meters) and when the ballast directly supports the weight of the drip shield and backfill. It is therefore, very important to conduct further study and field tests to determine the actual allowable bearing capacity for compacted tuff at the emplacement drift invert conditions.

- Bearing capacity failure will not occur for the case of one tie under the weight of WP/pallet only, if using the nominal allowable bearing capacity. However, under the same condition, bearing capacity failure will occur if the weight of drip shield and backfill is included.

- The ballast pressure under the drip shield legs supporting the weight of the drip shield and backfill is very high, i.e., more than three times higher than the upper bound bearing capacity. In order to prevent the bearing capacity failure at the base angle of the drip shield legs, an increase of the base angle width is necessary.

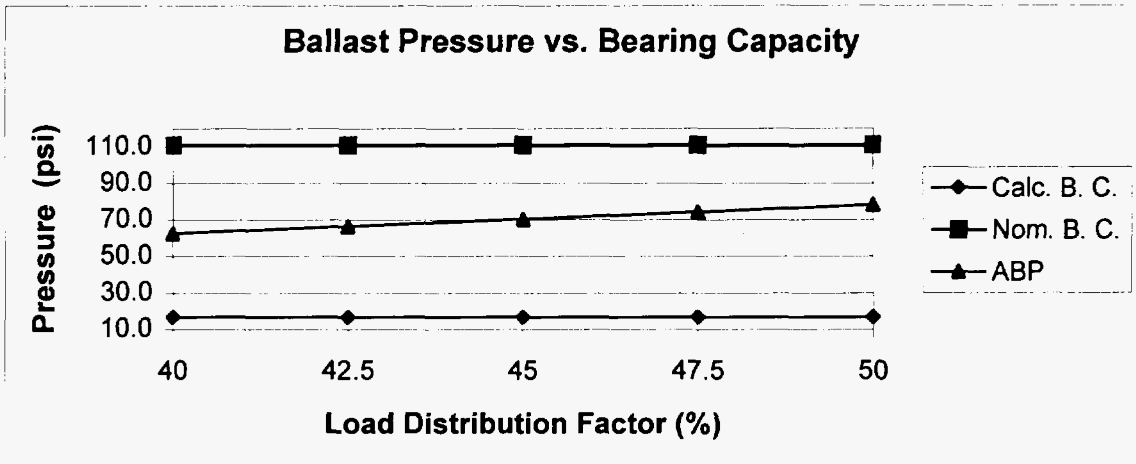

Figure 8. Comparison Between Pressure and Bearing Capacity of Ballast Under Steel Tie of C 9X20 – Under Moving Gantry with WP/Pallet

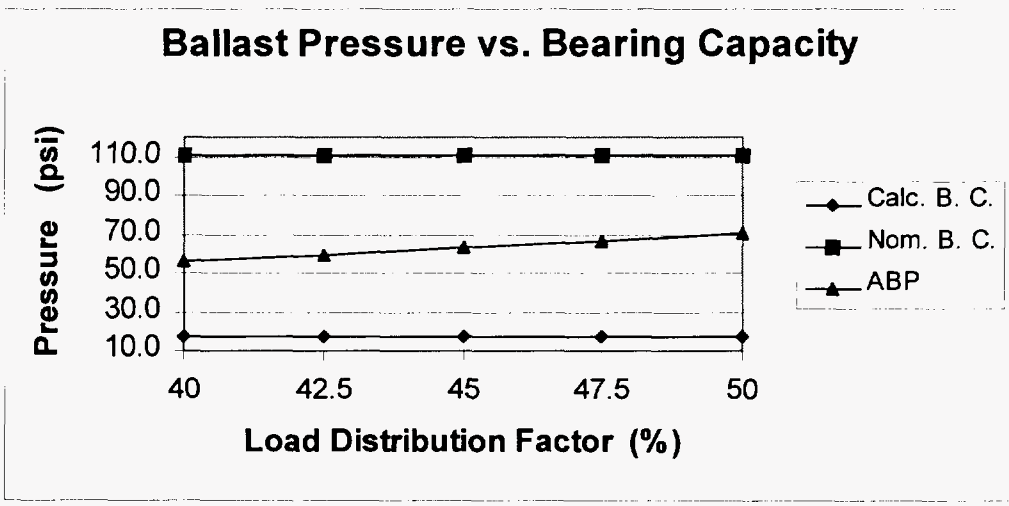

Figure 9. Comparison Between Pressure and Bearing Capacity of Ballast Under Steel Tie of C 10X20 - Under Moving Gantry with WP/Pallet

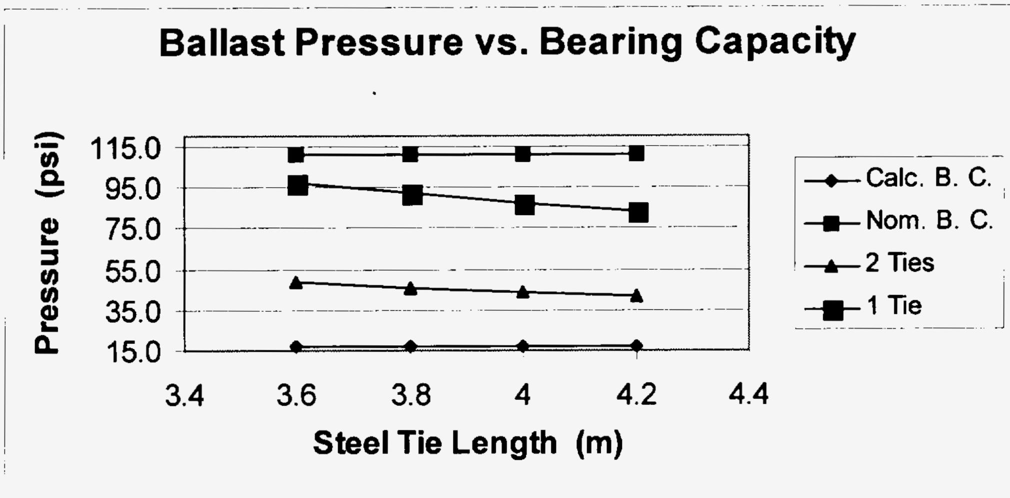

Figure 10. Comparison Between Pressure and Bearing Capacity of Ballast Under Steel Tie of C 9X20 – WP/Pallet Directly Supported by Ties-No Backfill

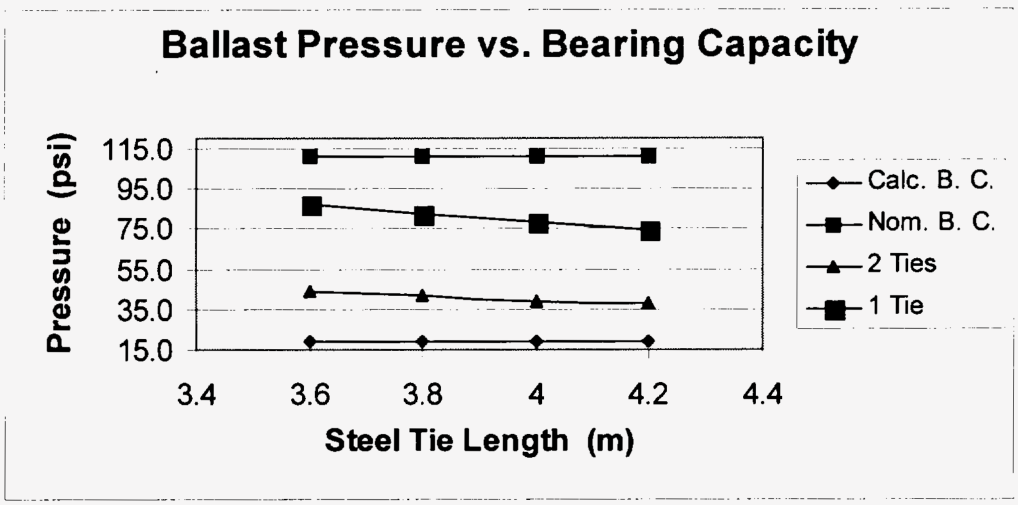

Figure 11. Comparison Between Pressure and Bearing Capacity of Ballast Under Steel Tie of C 10X20 – WP/Pallet Directly Supported by Ties-No Backfill

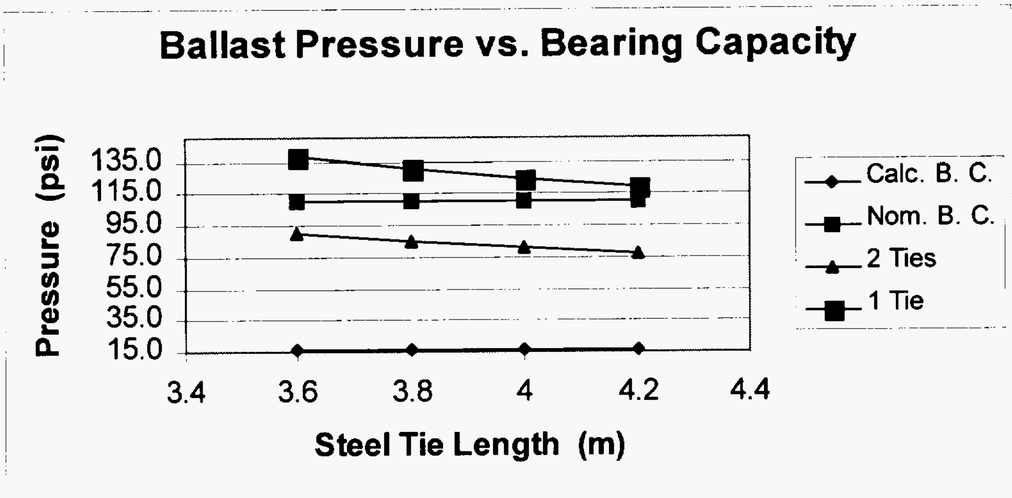

Figure 12. Comparison Between Pressure and Bearing Capacity of Ballast Under Steel Tie of C 9X20 – WP/Pallet Directly Supported by Ties – With Backfill

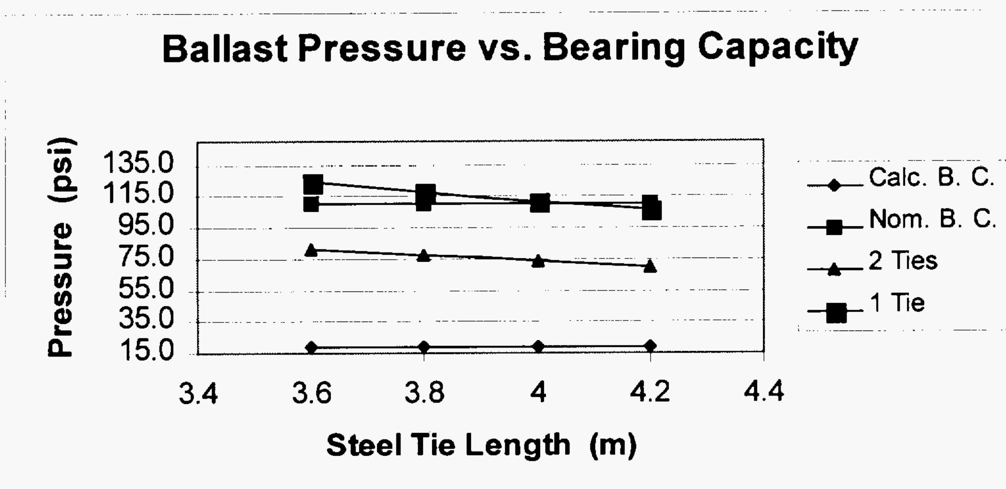

Figure 13. Comparison Between Pressure and Bearing Capacity of Ballast Under Steel Tie of C 10X20 – WP/Pallet Directly Supported by Ties – With Backfill

7.3.4 Potential Seismic Impact

The largest potential danger to track and roadbed in an earthquake is from failures in the subgrade due to slumping or liquefaction of the soils (AREA 1997, p. 9-1-23). Since the subgrade in the emplacement drift is a strong rock mass, basically in a dry condition, the potential for slumping or liquefying of the soils is unlikely.

Depending on the direction of seismic wave propagation with respect to the drift alignment, the track and ballast may be subjected to dynamic strains caused by an earthquake. The strain level is not expected to be damaging to track or ballast. An earthquake-induced lateral displacement of ballast materials is expected to be insignificant. The reason is that underground structures such as tunnels and their lining or reinforcement systems are constrained by the surrounding medium and do not move independently of the surrounding rock. In reality, the underground structures display significantly greater degrees of redundancy due to the confinement from the ground compared to surface structures, which are generally unsupported above their foundation.

During the shaking process the stability of the ties and ballast will be momentarily weakened (AREA 1997, p. 9-1-23). The drift invert returns to its pre-seismic stage upon the ceasing of the earthquake. Since the ballast is well graded and highly compacted, the impact of seismic motion on its stability will probably be insignificant. Further study needs to be performed to investigate the potential failure mechanisms under seismic motion, especially when the gantry carrying the WP/pallet is moving while the earthquake is occurring.

7.3.5 Proper Compaction

The engineering properties of the TBM muck will be improved through compaction. Compaction forces the particles together and increases density. This repositioning increases the internal friction between particles and thereby produces increased shear resistance in the compacted material (Barksdale 1991, p. 3-25). Compaction to a high density level is the best known and most economical method of developing stability in crushed aggregate bases (Barksdale 1991, p. 15-26). High compactibility is required for high bearing capacity of the crushed rock. The ability of an aggregate (or crushed rock) to sustain high compaction depends mainly on how well it is graded. A well graded rock ballast gives maximum density when properly compacted, which, in turn, will increase its load bearing capacity.

The crushed rock invert materials should be compacted with roller vibration in a multiple lift (or layer) operation when such a compaction effort is suitable. Each layer should be sufficiently thin to avoid segregation. In confined areas, such as around steel sets, a light self-propelled vibratory roller or vibrating tamping equipment should be used. The compaction effort should be characterized in terms of the relative density properties.

Water is usually used as lubricant agent during compaction to help the grains to attain a more efficient packing and thus increase the dry density. The amount of water to be used should be controlled to not exceed the optimum moisture content. In order to minimize the introduction of water to emplacement drift, compaction under dry condition or with minimum water may need to be considered. However, dust generation may be a problem in this situation. Further study in this aspect is necessary.

7.3.6 Ballast Thickness

For conventional railway track construction, a minimum of 12 inches of top ballast under ties and 6 inches of sub-ballast should be provided to give proper support to ties in a main-line track. However, this required thickness may vary over the length of a railway line depending on the traffic conditions and the strength in subgrade (AREA 1997, p. 1-1-30). A reduced ballast thickness of 6 to 8 inches (152 to 203 mm) is sometimes employed on tracks with low traffic volumes or light loading conditions (Barksdale 1991, p. 11-57). A minimum thickness of 400 mm of track construction depth under the rail to invert (i.e., bedrock in the current study) is required (Edwards 1990, p. 100).

The gantry, carrying a WP/pallet assembly, travels at a maximum speed limited to 150 ft/min (1.7 miles/hr) (CRWMS M&O 2000g, Section 6.5). This is a very low speed compared with the typical speed of operating trains. Additionally, the traffic frequency for waste package/pallet transportation in the emplacement drift is 3 WP/day (CRWMS M&O 2000g, Section 6.5, p. 61 of 77), which is also very low compared with main line railway traffic. Moreover, the subgrade (i.e., bedrock) under the crushed ballast is a very strong tuff rock. It is, therefore, reasonable to consider 400 mm as the proper thickness of ballast under the rail in this study. It should be pointed out that the final ballast thickness will not be determined until further study and tests are conducted.

7.3.7 Calculation of Average Ballast Pressure

Calculation of Average Ballast Pressure (ABP) (in psi) at Tie Face under Gantry Wheel Loading

ABP = [2P(1+IF/100)(DF/100)]/A (in psi)

where:
P = Wheel loading in lb
IF = Impact factor for track = 33V/100D (in percent)
DF = Distribution factor in percent
A = Contact area of the tie = B x L
V = Velocity in miles per hour
D = Diameter of wheel in inches
B = Tie width in inches
L = Tie length in inches, unless otherwise noted

(1) For Steel Tie of C 9x20

(a). DF = 40

V	D	P	IF	DF	B	L	A	ABP	Remark
1.7	15.7	40793	3.6	40	9	60.0	540.0	62.6	L = 1.52 m

(b). DF = 42.5

V	D	P	IF	DF	B	L	A	ABP	Remark
1.7	15.7	40793	3.6	42.5	9	60.0	540.0	66.5	L = 1.52 m

(c). DF = 45

V	D	P	IF	DF	B	L	A	ABP	Remark
1.7	15.7	40793	3.6	45	9	60.0	540.0	70.4	L = 1.52 m

(d). DF = 47.5

V	D	P	IF	DF	B	L	A	ABP	Remark
1.7	15.7	40793	3.6	47.5	9	60.0	540.0	74.3	L = 1.52 m

(e). DF = 50

V	D	P	IF	DF	B	L	A	ABP	Remark
1.7	15.7	40793	3.6	50	9	60.0	540.0	78.2	L = 1.52 m

(2) For Steel Tie of C 10x20

(a). DF = 40

V	D	P	IF	DF	B	L	A	ABP	Remark
1.7	15.7	40793	3.6	40	10	60.0	600.0	56.3	L = 1.52 m

(b). DF = 42.5

V	D	P	IF	DF	B	L	A	**ABP**	Remark
1.7	15.7	40793	3.6	42.5	10	60.0	600.0	59.8	L = 1.52 m

(c). DF = 45

V	D	P	IF	DF	B	L	A	**ABP**	Remark
1.7	15.7	40793	3.6	45	10	60.0	600.0	63.4	L = 1.52 m

(d). DF = 47.5

V	D	P	IF	DF	B	L	A	**ABP**	Remark
1.7	15.7	40793	3.6	47.5	10	60.0	600.0	66.9	L = 1.52 m

(e). DF = 50

V	D	P	IF	DF	B	L	A	**ABP**	Remark
1.7	15.7	40793	3.6	50	10	60.0	600.0	70.4	L = 1.52 m

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8. CONSTRUCTABILITY

8.1 GENERAL

The primary constructability issue is the confined space for underground work and related logistics for the handling, transporting, and placing materials within that confined space. Constructability of the invert configurations for the emplacement drift invert is discussed in detail in Section 6.6 of CRWMS M&O 2000a. Discussion is limited below to the features of the options developed for reducing the amount of steel used in the drift invert.

8.2 FABRICATION AND INSTALLATION OF STEEL MATERIALS

Fabrication and installation of steel materials for the emplacement drift invert is readily achievable. Fabrication of steel components for the steel invert with ballast (Figures 1 and 2) and the steel tie with ballast invert (Figures 3 and 4) that are made of ASTM A 709/A 709M steel will be required. This structural steel material is a weathering type steel with an enhanced atmospheric corrosion resistance for use in bridges. This high performance steel is the most suitable of the carbon steels for weathering properties without considering the stainless and alloy products. ASTM A 709/A 709M, Grade HPS 70W has a yield strength of 485 MPa (70 ksi) and is specified for plate to 100 mm (4 inches) thickness only. Steel shapes are not rolled in this grade of steel. Structural shapes for the invert frame and ties will require fabrication from selected steel plate.

Installation of the required materials for the emplacement drift invert will be time consuming and labor intensive, but generally not difficult. Safety practices for working and accessing the work area will require special consideration because of the numerous activities required during the installation process and because of the uneven surfaces and exposed tripping hazards.

8.3 PROCESSING AND INSTALLATION OF CRUSHED TUFF BALLAST

A well-graded and properly compacted tuff ballast is indispensable to assure the satisfactory performance for the waste package transportation and placement. TBM muck from TSw2 formation must be screened to possess adequate size distribution. In addition, coarse TBM chips are usually very flat and elongated, and thus require crushing (Gertsch et al. 1993, p. 18).

The muck, most likely, will be processed into suitable ballast at the surface. The ballast will then be transferred underground, taken by conveyor and placed into the invert. The ballast will be compacted as described in Section 7.3.5.

The ballast supported invert (Figures 3, 4, 5, and 6) is more compatible with rectangular section tunnels than with circular bores (Edwards 1990, p. 100). The rectangular section provides better confinement of the ballast, which is desirable to prevent lateral movement when ballast is subjected to heavy loading. From the construction view, it is also preferable for the compaction process. Further study and tests are needed to determine whether it is necessary to excavate the bottom of the drifts to form a rectangular shape.

It should be noted that the tie dimension and spacing are very important with respect to the stability of compacted tuff ballast. As indicated in Figures 8 through 13, the pressure on ballast decreases with the increase of tie length and width. Moreover, in order to prevent the ballast movement under heavy loading, it is advisable to increase the tie length to reach to the wall of drifts. It may not be necessary to do so for every tie. Tie spacing is also an important factor affecting the stability of ballast to support the waste packages whether they are in motion or resting on the ground. It is desirable to decrease the tie spacing to reduce the pressure on ballast under the ties. However, if they are spaced sufficiently close together, the intersection of adjacent shear zones may decrease bearing capacity of each tie. Spacing between ties should be at least 1.5B (B is the width of tie) to minimize any reduction in bearing capacity (ASCE 1993, p. 10). More study and tests are needed to determine the optimum tie spacing for waste packages.

The placement of crushed tuff ballast for the all ballast invert (Figures 5 and 6) requires handling, processing, and installation as discussed above.

9. CONCLUSIONS

9.1 MODIFIED INVERT CONFIGURATIONS

Concepts developed in *Invert Configuration and Drip Shield Interface* (CRWMS M&O 2000a) were evaluated and options were developed for reducing the amount of steel in the emplacement drift invert.

9.2 INTERFACES

Interfaces with the emplacement drift invert materials of carbon steel and ballast were presented and discussed in Section 6.3 and are summarized below:

- Emplacement Drift: Waste package support hardware (pallet) and performance enhancing barriers (diffusive barrier, drip shield, and backfill, if used)

- Ground Control: Steel set ground control components

- Waste Emplacement/Retrieval: Emplacement Drift System's waste package support pallet and waste emplacement equipment

- Backfill Emplacement: Backfill emplacement equipment (if required)

- Subsurface Facility: Waste package emplacement and support (pallet)

9.3 INVERT OPTIONS

Invert options were developed based on reducing the amount of steel in the emplacement drift invert. Section 6, discusses the invert design loads and materials. A high-strength low-alloy corrosion-resistant steel, ASTM A 709/A 709 M, with a yield strength of 485 MPa (70 ksi) was selected for the steel materials. Crushed tuff was selected for the ballast materials. The emplacement drift invert option that is selected for use in this technical report is the steel invert with ballast. Two alternative options for the emplacement drift invert that substantially reduce the amount of steel have also been evaluated. Design analysis for each of the options, as deemed appropriate, is required to determine the suitability and compatibility of materials in the emplacement drift environment, the structural materials and related properties, and the interface relationships and related impacts. Additionally, fabrication requirements, material handling requirements, costs, constructability, and associated safety aspects must also be determined in detail. Materials for the design options were evaluated in Sections 7.2 for use of steel and Section 7.3 for the use of ballast. Results of these design evaluations are summarized below.

Steel Invert with Ballast–The steel invert with ballast is the option selected in this technical report for use in the potential repository. This concept relies on structural carbon steel members that have been framed to support the waste package/pallet assemblies, the *emplacement gantry*, the drip shields, and any backfill materials. All monitoring and emplacement equipment would operate on the installed steel gantry rails. This concept is an all-steel structural support system that is anchored with bolts to the tunnel invert. Figures 1 and 2 show elevation and perspective views, respectively. Evaluation in this report showed a reduction of steel materials. Some member sizes decreased relative to those shown in CRWMS M&O 2000a and are discussed in Section 7.2.1.

Constructing the invert segment with steel materials provides the least opportunity for settlement of the waste package/pallet assembly. The steel invert materials can be designed to be as stiff as necessary to prevent deflection in the steel support members and meet the prescribed tolerances for waste package settlement. Ballast materials of crushed tuff would be placed between and around the steel structural members to fill the invert space to approximately the top of the steel transverse and longitudinal support beams (Figure 2). Compaction of the ballast material would require minimal effort to ensure limited settlement over time. The ballast materials would not provide any major load support except perhaps for initial foot traffic and eventually for potential backfill materials that would contact the ballast in the limited area between the drip shield and tunnel walls.

Steel Tie With Ballast Invert–This option is a steel tie with ballast invert that uses ballast materials with structural steel ties to support the waste package/pallet assembly, the drip shields, the potential backfill materials, the emplacement gantry, and other emplacement equipment. Other emplacement equipment will be required for placing the drip shields and any backfill materials, and for performance monitoring. All emplacement equipment would operate on the installed steel rails. Figures 3 and 4 show elevation and perspective views, respectively. Ballast materials of crushed tuff would be compacted as described in Section 7.3.5, to provide a stable foundation for support of the structural steel ties that would be in direct contact with the waste package/pallet assemblies, the drip shields, the gantry rails, and the potential backfill materials. Compaction of the ballast materials would be sufficient to consolidate the materials to the point where settlement of the ballast over time would not be significant. However, compacted ballast, as the main support structure, may be susceptible to construction and material anomalies that may cause localized settlement. The compacted ballast invert may not always be capable of meeting prescribed tolerances for waste package settlement. These requirements must be considered in future analyses to determine if the steel tie with ballast invert concept is suitable for maintaining the waste package pallet assembly in position.

The steel tie with ballast invert provides a substantial reduction in steel materials. A system of steel channels replaces the steel frame.

All-Ballast Invert–This option is an all-ballast invert concept that uses ballast materials only to support the waste package/pallet assembly, the emplacement gantry, the drip shields, and any backfill materials. Other emplacement equipment required for the placing the drip shields and the potential backfill materials and the performance monitoring equipment will also be supported by the ballast. Figures 5 and 6 show elevation and perspective views, respectively. All emplacement equipment would operate directly on the surface of the ballast material. Ballast materials would be compacted as described in Section 7.3.5, to provide a stable foundation to support the waste package/pallet assembly, the drip shield, the emplacement equipment, and any backfill. Compaction of the ballast materials would be sufficient to consolidate the materials to the point where settlement of the ballast over time would not be significant. However, compacted ballast, as the main support structure, may be susceptible to construction and material anomalies that may cause localized settlement. The compacted ballast invert may not always be capable of meeting prescribed tolerances for waste package settlement. These requirements must be considered in future analyses to determine if the all-ballast invert concept is suitable for maintaining the waste package pallet assembly in position.

Detailed analyses for the above options will be required to determine their suitability for waste emplacement. New concepts of and analysis for waste emplacement equipment will also be required to utilize the all-ballast invert, which requires track- or wheel-mounted equipment.

The all-ballast invert eliminates all steel from the emplacement drift invert.

9.4 MATERIALS

Materials for the design options for the emplacement drift invert were evaluated in Sections 6.4, 7.2 and 7.3 and are summarized below.

Steel Materials– Materials for the steel frame of the emplacement drift invert and for the gantry rail support beams will consist of high-strength low-alloy structural steel conforming to ASTM A 709/A 709M and ASTM A 242/A 242M. ASTM A 759 steel will be used for the gantry rails. ASTM A 709/A 709M steel will also be used for the steel ties in the alternative option. Compatibility of the carbon steel invert materials with the pallet and the drip shield materials requires evaluation. Analysis is also required to identify suitable materials to be used for separation barriers, if needed, between the invert materials and the pallet and drip shield materials.

Ballast Material–Emplacement drift invert ballast materials will consist of crushed tuff. Requirements for the ballast materials were discussed and presented in Section 7.3, and material selection criteria and characteristics were developed.

Laboratory testing is recommended to assess the crushed tuff ballast materials to ensure that the criteria for gradation and compaction can be achieved.

Steel Invert with Ballast–The invert ballast materials for this option do not require extensive compaction, only moderate vibration to consolidate the materials and minimize settlement is required. Testing will be required to determine the amount of compaction that is needed for the ballast materials to achieve minimal support characteristics.

Steel Tie With Ballast Invert–The invert ballast materials of crushed tuff will have a sufficient particle size and will require compaction to provide structural support for the steel tie and gantry rail, the waste package/pallet assembly, the drip shield, and any backfill (Figures 3 and 4). Testing will be required to determine gradation and compaction effort needed to achieve the required support strength.

All-Ballast Invert–The invert ballast material must be compacted to achieve a bearing capacity that would support the emplacement gantry, the waste package pallet assemblies, the drip shields, and the potential backfill materials (Figures 5 and 6). Testing will be required to determine gradation and compaction effort needed to achieve the required support strength.

9.5 CONFORMANCE OF DRIFT INVERT OPTIONS TO INPUTS

Table 7 shows the allocation of design inputs to the drift invert options developed in this report. Design inputs are met except where the use of carbon steel, a carbon steel frame, and/or the steel design manual are not applicable (N/A) and where the use of the Subsurface Excavation System for placement of the invert is not practicable (i.e., N/A).

The all-ballast invert does not comply with the *Emplacement Drift System Description Document* (CRWMS M&O 2000e) or the *Monitored Geologic Repository Project Description Document* (CRWMS M&O 2000j) which clearly require carbon steel structural members as part of the invert. This design option, should it be selected, will require changes to the above documents.

TABLE 7. CONFORMANCE OF DRIFT INVERT OPTIONS TO INPUTS

INPUTS	CONFORMANCE SECTION		
	INVERT OPTIONS		
	STEEL INVERT WITH BALLAST	STEEL TIE WITH BALLAST	ALL-BALLAST
4.1 PARAMETERS (Section)			
4.1.1 Steel Material Properties	6.4.1, 7.2.1	6.4.1, 7.2.1	N/A
4.1.2 Ballast Material Properties	7.3.2	7.3.2	7.3.2
4.1.3 Design Dead and Live Loads	4.4.1, 6.2, 7.1.1, 7.2, 7.2.1	4.4.1, 6.2, 7.1.1, 7.2, 7.2.1	4.4.1, 6.2, 7.1.1, 7.2, 7.2.1
4.1.4 Seismic Loads	4.4.2, 7.1.2, 7.2.1	4.4.2, 7.1.2, 7.2.1	4.4.2, 7.1.2, 7.2.1
4.2 CRITERIA (Section)			
4.2.1 Emplacement Drift System			
4.2.1.1 (TBV-284)	7.3.2	7.3.2	7.3.2
4.2.1.2	6.4.1	6.4.1	N/A
4.2.1.3	6.4.2	6.4.2	6.4.2
4.2.1.4	6.2, 7.2.1	6.2, 7.2.1	6.2, 7.2.1
4.2.1.5	7.2.1	7.2.1	N/A
4.2.1.6	4.3	4.3	4.3
4.2.1.7	6.2, 7.2.1	6.2	6.2
4.3 CPAs (Section)			
4.3.1	7.3.2	7.3.2	7.3.2
4.3.2	6.2, 6.4.2, 7.3, 7.3.2	6.2, 6.4.2, 7.3, 7.3.2	6.2, 6.4.2, 7.3, 7.3.2
4.4 OTHER ASSUMPTIONS (Section)			
4.4.1	6.2, 7.1.1	6.2, 7.1.1	6.2, 7.1.1
4.4.2 (TBD-241 TBV-273)	4.4.1, 7.1.2, 7.2.1, 7.3.3.2	4.4.1, 7.1.2, 7.2.1, 7.3.3.2	4.4.1, 7.1.2, 7.2.1, 7.3.3.2

9.6 CONSTRUCTABILITY

Constructability for the three basic invert design configurations was evaluated in Section 6.6 of CRWMS M&O 2000a. The evaluation ranked the concepts for ease of construction as:

- Modified steel invert with ballast: Most complex
- Steel tie with ballast invert: Less difficult than the modified steel invert
- All-ballast invert: Least difficult.

Detailed discussion of constructability for the invert design configurations is shown in Section 6.6 of CRWMS M&O 2000a.

Steel materials selected for the steel invert with ballast and the steel tie with ballast invert are ASTM A 709/A 709M, Grade HPS 70W with lighter steel members being of ASTM A 242/A 242M. This structural steel material is a weathering type steel with an enhanced atmospheric corrosion resistance for use in bridges. This high performance steel is the most suitable of the carbon steels for weathering properties without considering the stainless and alloy products. Steel shapes are not rolled in the A 709 grade of steel and structural shapes for the invert frame and ties will require fabrication from selected steel plate.

Crushed tuff materials used for the ballast will require processing, screening and washing, to achieve a gradation suitable for compacting into a fill that can support the steel tie and rail or can support directly the waste package/pallet assembly and a delivery gantry. The average ballast pressure under one tie loaded with a waste package, Table 1, does not exceed the upper bound of the allowable bearing capacity, Section 7.3.3.3, of the crushed tuff material. The average ballast pressure under two ties, similarly loaded, is considerably less as shown in Table 2. The average ballast pressure under one tie loaded with a waste package, drip shield and backfill, Table 3, exceed the upper bound of the allowable bearing capacity. The average ballast pressure under two ties, similarly loaded, is considerably less as shown in Table 4.

Current design of the pallet beam width 552.4 mm (21.75 inches) and pallet beam spacing of 3042.4 mm (4147.2–2x552.4) between inside face of beams (CRWMS M&O 2000k, Figure III-1) is not compatible with the tie spacing of 508 mm (20 inches) in order to always have each pallet beam bearing on two ties. With waste packages being spaced at 10 cm between ends and having different lengths the potential will exist that the pallet beam may bear on only one tie. Using a C10x20 the distance between ties is 254 mm (10 inches). It does not appear practical to place the ties edge to edge. However, if the pallet beam width could be increased and the edge to edge distance between ties reduced the pallet beam may have the potential to more frequently rest on two ties and the bearing pressure would be reduced. Additional tests and studies are needed to determine the potential bearing capacity and required depth of crushed tuff.

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10. REFERENCES

10.1 DOCUMENTS CITED

Barksdale, R.D., ed. 1991. *The Aggregate Handbook.* Pages 3-25,11-7,11-57,15-26. Washington, D.C.: National Stone Association. TIC: 248354.

CRWMS M&O 1997. *Preliminary Waste Package Transport and Emplacement Equipment Design.* BCA000000-01717-0200-00012 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980511.0131.

CRWMS M&O 1998. *Emplacement Drift Invert Structural Design Analysis.* BBDC00000-01717-0200-00001 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980625.0366.

CRWMS M&O 1999. *Ex-Container and Backfill WP# 12012124M8.* Activity Evaluation, October 1, 1999. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19991020.0138.

CRWMS M&O 2000a. *Invert Configuration and Drip Shield Interface.* TDR-EDS-ST-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000505.0232.

CRWMS M&O 2000b. *Waste Emplacement/Retrieval System Description Document.* SDD-WES-SE-000001 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000823.0002.

CRWMS M&O 2000c. *Structural Calculations of the Drip Shield Statically Loaded by the Backfill and Loose Rock Mass.* CAL-XCS-ME-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000216.0098.

CRWMS M&O 2000d. *Backfill Emplacement Analysis.* ANL-BES-MG-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000418.0816.

CRWMS M&O 2000e. *Emplacement Drift System Description Document.* SDD-EDS-SE-000001 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000803.0348.

CRWMS M&O 2000f. *Ground Control System Description Document.* SDD-GCS-SE-000001 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000803.0355.

CRWMS M&O 2000g. *Bottom/Side Lift Gantry Conceptual Design.* ANL-WES-ME-000003 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000420.0399.

CRWMS M&O 2000h. *Backfill Emplacement System Description Document.* SDD-BES-SE-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000210.0074.

CRWMS M&O 2000i. *Subsurface Facility System Description Document.* SDD-SFS-SE-000001 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000807.0078.

CRWMS M&O 2000j. *Monitored Geologic Repository Project Description Document.* TDR-MGR-SE-000004 REV 01 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000713.0361.

CRWMS M&O 2000k. *Design Analysis for the Ex-Container Components.* ANL-XCS-ME-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000525.0374.

CRWMS M&O 2000l. *Emplacement Drift Invert-Low Steel Evaluation.* Development Plan TDP-EDS-ST-000002 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000531.0126.

DOE (U.S. Department of Energy) 2000. *Quality Assurance Requirements and Description.* DOE/RW-0333P, Rev. 10. Washington, D.C.: U. S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20000427.0422.

Edwards, J.T. ed 1990. *Civil Engineering for Underground Rail Transport.* p. 100 only. London, England: Butterworth & Co. Copyright Requested Library Tracking Number-248352

Gertsch, R. E.; Fjeld, A.; Asbury, B.; and Ozdemir, L. 1993. *Construction Applications for TSw2 TBM Cuttings at Yucca Mountain.* Golden, Colorado: Colorado School of Mines. ACC: NNA.19940317.0013.

Merritt, F.S.; Loftin, M.K.; and Ricketts, J.T., eds. 1996. *Standard Handbook for Civil Engineers.* 4th Edition. New York, New York: McGraw-Hill. TIC: 248762.

Winterkorn, H. F., and Fang, H-Y. 1975. *Foundation Engineering Handbook.* Pages 126-129, 256 & 263. New York, New York. Van Nostrand Reinhold Company. TIC: 248400.

10.2 CODES, STANDARDS, REGULATIONS AND PROCEDURES

AISC (American Institute of Steel Construction) 1995. *Manual of Steel Construction - Allowable Stress Design.* 9th Edition, 2nd Revision, 2nd Impression. Chicago, Illinois: American Institute of Steel Construction. TIC: 240772.

AP-2.14Q, Rev. 0, ICN 1. *Review of Technical Products.* Washington, D.C.: DOE, Office of Civilian Radioactive Waste Management (OCRWM). ACC: MOL.20000405.0477.

AP-3.4Q, Rev. 1, ICN 3. *Level 3 Change Control.* Washington, D.C.: DOE, OCRWM. ACC: MOL.20000525.0376.

AP-3.11Q, Rev. 1, ICN 1. *Technical Reports.* Washington, D.C.: DOE, OCRWM: ACC: MOL.20000714.0549.

AP-3.15Q, Rev. 1, ICN 2. *Managing Technical Product Inputs.* Washington, D.C.: DOE, OCRWM. ACC: MOL.20000713.0363.

AP-SV.1Q, Rev. 0, ICN 2. *Control of the Electronic Management of Information.* Washington, D.C.: DOE, OCRWM. ACC: MOL.20000831.0065.

AREA (American Railway Engineering Association) 1997. *Manual for Railway Engineering.* Volume 1. Washington, D.C.: American Railway Engineering Association. TIC: 233847.

ASCE (American Society of Civil Engineers) 1993. *Bearing Capacity of Soils.* Pages 1, 2, 10, 26, 27, 36, 37. New York, New York: American Society of Civil Engineers. TIC: 241549.

ASTM (American Society for Testing and Materials) A 36/A 36M-97a. 1998. *Standard Specification for Carbon Structural Steel.* West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 243523.

ASTM A 240/A 240M-99b. 2000. *Standard Specification for Heat-Resisting Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels.* West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 248529.

ASTM A 242/A 242M-98. 1998. *Standard Specification for High-Strength Low-Alloy Structural Steel.* West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 248531.

ASTM A 572/A 572M-99a. 1999. *Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel.* West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 246273.

ASTM A 588/A 588M-94. 1994. *Standard Specification for High-Strength Low-Alloy Structural Steel with 50ksi (345MPa) Minimum Yield Point to 4 inches (100mm) Thick.* Philadelphia, Pennsylvania: American Society for Testing and Materials. TIC: 241422.

ASTM A 709/A 709M-00. 2000. *Standard Specification for Carbon and High-Strength Low-Alloy Structural Steel Shapes, Plates, and Bars and Quenched-and-Tempered Alloy Structural Steel Plates for Bridges.* West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 248751.

ASTM C 88-99a. 1999. *Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate.* West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 246402.

ASTM C 117-95. 1998. *Standard Test Method for Materials Finer than 75μm (No. 200) Sieve in Mineral Aggregates by Washing.* Philadelphia, Pennsylvania: American Society for Testing and Materials. TIC: 242992.

ASTM C 127-88 (Reapproved 1993). 1998. *Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate.* Philadelphia, Pennsylvania: American Society for Testing and Materials. TIC: 242992.

ASTM C 131-96. 1998. *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.* Philadelphia, Pennsylvania: American Society for Testing and Materials. TIC: 242992.

ASTM C 142-97. 1998. *Standard Test Method for Clay Lumps and Friable Particles in Aggregates.* West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 248359.

ASTM C 535-96. 1998. *Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.* Philadelphia, Pennsylvania: American Society for Testing and Materials. TIC: 242992.

ASTM D 4791-99. 1999. *Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate.* West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 248394.

ASTM G 101-97. 1997. *Standard Guide for Estimating the Atmospheric Corrosion Resistance of Low-Alloy Steels.* West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 248533.

NRC (U.S. Nuclear Regulatory Commission) 1987. *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants.* NUREG-0800. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 203894.

QAP-2-0, Rev. 5, ICN 1. *Conduct of Activities.* Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19991109.0221.